Mechanical Characterization of Flexible and Stretchable Electronic Substrates

Proefschrift

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door

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Geboren de Wanzai, Jiangxi, China
To my wife: Zou Suqin
To my parents
To my brothers and sisters
Summary

Conventional IC packages form a rigid shell around silicon IC dies. Their purpose is to provide environmental protection, electrical interconnect and heat dissipation. Despite the fact that majority of current silicon IC's are realized in a very thin top layer of the silicon substrate (<10µm), the typical thickness of packaged IC dies generally exceeds 150 µm. Continuous system miniaturization and performance improvement leads to new mass volume applications where packaging technology has to be reviewed. Here only the essential part of silicon IC’s i.e. the 10-20 µm thick top layer could be retained after thinning of the wafer. In the wafer thickness range of 10–30 µm, silicon substrates become mechanically flexible and consequently offer a large field of new products and innovative applications.

A promising development of flexible and stretchable substrates is proposed. 3D deformable electronics could be realized by the vertical thinning and lateral partitioning of the silicon substrate on sub-millimeter scale. The partitions or so-called segments can be combined to larger electronic systems by connecting many of these through electrical bridges. By varying the dimensions and/or the geometry of the segments and the gap size in between the segments as well as the geometry of the electrical bridges, the level of deformations can be controlled. In practical realization such patterned silicon structures have to be embedded/sandwiched into a polymer film to provide environmental protection and to prevent mechanical damage because of overstretching.

In order to evaluate the influence of segment size and gap size on the occurrence of failure under bending and stretching, so-called 1st generation flexible and stretchable test samples were designed and prepared. The test samples being considered have hexagonal or square segments (varying in size from 150 to 2000 µm) being embedded in polyimide. Special tensile and bending test tools were designed and fabricated to in situ observe the occurrence of cracks during loading. An optical microscope with the possibility of recording and analysing the digital images is used for establishing the crack density and width. Experimental and simulation results for the onset of cracking are quite disappointed. It is shown that the first cracks appear in the oxide layers in the gaps in between the silicon segments. The crack density appears to increase
rapidly at early stage of loading and subsequently increases slightly. However, the width of the cracks appears to increase steadily during loading. Only at higher (mean) deformations the cracks propagate (or are generated) within the silicon itself. The onset of cracking depends significantly on the silicon segmentation size. The segment size and gap size also affects the crack density and the crack width at larger (mean) deformation levels. There is no crack detected for bending around glass cylinders (even not for the cylinder with the smallest diameter, \( \Phi = 2 \) mm) for samples with a square segment with 450 \( \mu \)m side length and 120 \( \mu \)m gap size and for samples with a hexagonal segment with 300 \( \mu \)m side length and 40 \( \mu \)m gap size. The remaining bending results show that for other samples with square segments failure always occurs for bending around the glass cylinder with the smallest diameter (\( \Phi = 2 \) mm). From the tensile testing as well as from the simulation results we learned that occurrence of cracks in the oxide layers severely limits the stretchability of the substrates.

Because of the early damage initiation found for the 1st generation samples, a modified design was proposed and worked out. So-called 2nd generation samples were designed and fabricated with fully segmented polycrystalline silicon segments with flexible aluminium interconnections which are supported by flexible poly-silicon support structures. Again polyimide was used as the embedding material. The samples being considered have varying segment sizes (from 150 to 450 \( \mu \)m) and varying gap sizes (from 20 to 200 \( \mu \)m). Various (more or less) sinusoidal interconnections were chosen with various numbers of half waves and various wave amplitudes. When the samples were bent around the (smallest) cylinder with 2 mm diameter, no damage of the segments was detected. Resistance measurements did not show a resistance increase larger than 5%. Compared to the 1st generation samples, for tensile testing of the 2nd generation samples the (mean) strain at onset of failure (which now is segment cracking) is significantly improved. In order to gain more insight into the occurrence of interconnection failures various FE simulations were performed for wave-shaped interconnections of samples with square segments (under stretching only). The local model used is made up from a single gap (of polyimide) with metallic interconnection and poly-silicon support structure in between two embedded segments. Comparison of the experimentally obtained strain values for the resistance change of 5% and the “sample mean strain” at (assumed) onset of failure, did not give a good match. Apparently the assumed onset of failure, defined by reaching the ultimate strength in the aluminium (that only occurs at some local) is not a good measure for the degradation of the electric conductivity. The “work of plastic deformation” might be better correlated to the change in resistance. The sinusoidal wave interconnection shows the best electrical performance
compared to the straight interconnection and the semi-circular interconnection. The influence of wave amplitude, number of half waves and line width of the sinusoidal interconnection is explored. However, the sample mean strain at onset of interconnection failure appears to be limited to a few percents only. From both the experiments and the interconnection FE simulations it is concluded that again insufficient flexibility is obtained for all considered interconnection shapes. It is believed that this is caused by the embedding of the segments and interconnections within the polyimide. For this reason in Chapter 4 embedding in a much softer material is worked out. Also the case of a completely free interconnection (not embedded) is considered (in Chapter 5). In this manner a new concept of future flexible and stretchable substrates is introduced.

In the concept of “Future flexible and stretchable substrates I” (Chapter 4), the segments and interconnections are fully embedded into ELASTOSIL RT 601 (a kind of silicone rubber, from now to the whole thesis, the silicone rubber is ELASTOSIL RT 601). Adequate material models for silicone rubber are essential for getting insight into the mechanical behavior of the new design through FE modeling. In particular, FE modeling is used to forecast possible failure. The mechanical properties of silicone rubber were characterized by various methods including tensile testing, cyclic tensile testing and DMA. The ultimate tensile elongation of the silicone rubber foil can reach about 176% at room temperature. Visco-elastic behaviour of the silicone rubber at room temperature is not relevant. The 3rd order Mooney model was selected for the constitutive description of the silicone rubber for the FE simulations.

Based on the FE simulation results for the “future flexible and stretchable substrate I” it is expected that when increasing the mean sample strain, first the Si support structure will fail and subsequently the silicone rubber will fail during tensile loading. Failure of the Si-segments is likely not to occur at all. Compared to the 2nd generation substrates, the concept the “future flexible and stretchable substrate I” only gives an improvement of (about) a factor 2 for the main strain level at failure occurrence. The limiting factor for the improvement is the disappointing behavior of the Si-support structure. Apparently, the embedment of the Si-support structure by rubber very much reduces the “spring” behavior of the sinusoidal support structure. Therefore, a major improvement is suggested for the “Future Flexible and Stretchable Substrate II”, by not completely embedding the interconnection by silicone rubber, but only sandwiching this structure between two silicone rubber foils.

For the concept of “Future Flexible and Stretchable Substrate II” the aluminum wave interconnections are replaced by copper wave interconnections because the better mechanical
and electronic performance of copper. Free-standing interconnection copper lines (without support structures), sandwiched in between silicone rubber sheets, connect the Si-segments. Three types of the interconnections, meander shaped, horseshoe shaped and meshed shaped, were designed with various parameter sets. Simulations for these basic parts were performed to evaluate the influence of the geometric parameters on the flexibility and stretchability. The free-standing interconnection shapes and their geometric parameters have significant influence on the stretchability. From the three types of interconnections being considered, the meander shaped design appears to be most favourable. Compared to the results for the “Future Flexible and Stretchable Substrate I” it can be concluded that an enormous improvement of the stretchability of the interconnect structure is found. It is realized that because of the enormous flexibility of the meander shaped interconnection design, the maximum mean strain of the substrate is limited by the maximum mean strain that other parts can withstand. Here it should be noted that the maximum mean strain of the silicone rubber sheets is limited to about 176%, or less. With this elongation limit the (found) most favourable meander interconnection (W=5 μm, R=100 μm and α=30 degree) will behave fully elastic and thus will not be damaged, even not under cyclic elongation.
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## Abbreviations

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<th>Full Form</th>
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<tr>
<td>3D</td>
<td>3 dimensions</td>
</tr>
<tr>
<td>BHF</td>
<td>Buffered Hydrofluoric Acid</td>
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<td>BioFlex</td>
<td>Biocompatible Flexible Electronic Circuits</td>
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<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide Semiconductor</td>
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<tr>
<td>DMA</td>
<td>Dynamic Mechanical Analysis</td>
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<tr>
<td>FE</td>
<td>Finite element</td>
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<td>FEM</td>
<td>Finite element method</td>
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<tr>
<td>IC</td>
<td>integrated circuit</td>
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<tr>
<td>LPCVD</td>
<td>Low Pressure Chemical Vapor Deposition</td>
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<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapor Deposition</td>
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<tr>
<td>PI</td>
<td>polymide</td>
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<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
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<tr>
<td>SMD</td>
<td>Surface-mount components</td>
</tr>
<tr>
<td>SOA</td>
<td>Silicon On Anything</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon On Insulator</td>
</tr>
<tr>
<td>STELLA</td>
<td>Stretchable ELectronics for Large Area applications</td>
</tr>
<tr>
<td>SWEET</td>
<td>Stretchable and Washable Electronics for Embedding</td>
</tr>
<tr>
<td>TMAH</td>
<td>Tetramethyl ammonium hydroxide</td>
</tr>
<tr>
<td>TMAOAH</td>
<td>Tetramethylammonium hydroxide</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
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Chapter 1

Introduction

1.1 State of the art

The semiconductor industry is driven by the continuous push for miniaturization (following Moore’s law), enabling the creation of increasingly complex electronic products. In the past, the major application areas for electronics industry were computing, automation, communication and consumer products. A crucial part of any electronic product is an integrated circuit (IC) usually fabricated using silicon technology. The resulting silicon IC dies are packaged in various IC packages. Their main purpose is to provide environmental protection, electrical interconnect and heat dissipation. Traditionally IC packages form a rigid protective shell around silicon IC dies. Despite the fact that majority of current silicon ICs are realized in a very thin top layer of the silicon substrate (<10µm), the typical thickness of packaged IC dies exceeds 150 µm. The main reasons for this are following: front-end silicon processing relies on single-crystalline silicon substrates having sufficient thickness for reliable wafer handling even at very high temperatures (>1000°C); post-fabrication substrate thinning below 100 µm is not a trivial operation; and finally, handling of thin substrates would require introduction of new techniques.

Today, microelectronics is part of almost all processes and trends in the modern society. These include increased mobility, eco-awareness, the ageing population and increased importance of wellness and health. As a result also less trivial options in silicon technology and IC packaging are being explored. Flexible electronics has attracted a lot of attention for its
applications in paper-like displays, sensors/actuators, medical devices, and RF identification. It is believed that in the future many electronic assemblies on rigid substrates will be replaced by mechanically flexible or even stretchable alternatives. This is a consequence of the ambient intelligence vision where the citizen carries along more and more electronic systems, near the body, on or even inside the body. These systems must be light weighted, must preferably take the shape of the object in which they are integrated, and must even follow all complex movements of these objects, hence there is need for stretchability and flexibility. Because of this need for stretchability and flexibility of microelectronic substrates various research centres and research groups are involved in investigation of new types of stretchable and/or flexible substrates.

**Flexible substrates**

A first group of developments focuses towards formation of flexible substrates (here the stretchability is limited), which can be applied stand alone or can be wrapped on a cylindrically curved object. The electronic circuits are developed on flexible polymer substrates, such as by applying printing techniques [Y. Chen, 2003, Gerwin H, 2004, J. Huang, 2007]. The advantage of this kind of printed electronics might be in the low pricing due to large scale and fast production. The drawback of these techniques is that transistors made in this manner appear not to perform at the gigahertz speeds needed for advanced applications. Transistors with high-quality should be made on single-crystal silicon (instead of on polymers or on amorphous silicon) because electrons simply move faster in single-crystalline silicon [Dae-Hyeong Kim, 2008].

**Flexible and stretchable substrates**

A second group of developments focuses towards the formation of substrates that are not only flexible, but also stretchable. In principle these kinds of substrates can be wrapped on to doubly-curved objects as well.

In the European projects like STELLA (Stretchable EElectronics for Large Area applications, [STELLA project website]), SWEET (Stretchable and Washable Electronics for Embedding in Textiles, [SWEET project website]) and BioFlex (Biocompatible Flexible Electronic Circuits, [BioFlex project website]), stretchable substrates have been developed, using standard PCB manufacturing technologies, for stretchable interconnects with an elongation capability of up to 100%. Those stretchable interconnects can be used to produce stretchable electronic systems, using standard SMD components and soldering technologies. Embedded in biocompatible silicone rubber, these systems can be implantable or be a part of a
biomedical system. Different polymer types can be used for other types of applications like implantable biomedical systems, smart textiles, 3D shaped flexible or stretchable systems, strain absorbing systems, sensors, actuators, robotic skins, etc. It is possible to design more complex systems, including stretchable antennas and batteries, for wireless systems on the stretchable substrates. The STELLA project focuses on development of stretchable electronics for large area applications for use in healthcare, wellness and functional clothes, integrated electronics in stretchable parts and products. The goal of BioFlex is to focus on a new form of packaging and interconnection of implantable electronics. SWEET aims at the development of a technology platform for stretchable and washable electronic circuits and for embedding technologies of these circuits in textiles.

Actually, the STELLA, SWEET and BioFlex projects created polymer embedded flexible interconnections in which standard SMD components are included. However, these components are not flexible at all. An advantage of the inclusion of standard SMD components could be that these are commercially available in many kinds. A disadvantage is that because of the size of the standard SMD components and their inflexibility the lateral dimensions of the total substrates will be relatively large.

The goal of the present research is to investigate flexible substrates, where both the electronics and the interconnections are flexible. In this case the size of the electronic substrates can be very much reduced. The idea to realize real flexible substrates is to create electronic circuits on thinned silicon segments and have these connected by flexible and stretchable interconnections. This all is protected against environmental influences and against overstretching through embedment of the system of interconnected segments within a thin layer of a suitable polymer. The creation of this type of flexible and stretchable substrates is performed by transferring CMOS based circuits (these include the interconnections between segments) onto a suitable flexible polymer substrate. Details of the procedure being developed are described in Chapter 2 and 3.

Another parallel development of a flexible and stretchable substrate, which in some sense uses similar ideas and production steps as in the present research is reported by Rogers (John A. Rogers, e.a., 2008). He transferred ultra thin single-crystalline silicon to strained rubberlike substrates. After release of the straining the thinned silicon segments are buckled. The buckled segments allow for extension of the segments additionally to their flexibility.
1.2 Applications

Flexible and stretchable substrates developed in this project can be made of stamped, plated and, in many cases, laminated thin tapes that customers can use for a variety of purposes. Flexible substrate technology permits compact design, complex arrangements of fine structures and optimum heat management. For each application and requirement they are individually conceived and newly developed. This means that there are many challenges which have to be met. For example, we have to cope with various structures with surfaces that have three-dimensional textures. Also we have to do with several metallurgical and electrical features of the laminated alloy layers. Some possible future applications of flexible and stretchable substrates are:

Medical applications for identification purposes or as sensory nodes
- disposable wireless sensory nodes
- adhesive labels attached to the human skin
- implantable sensors built on flexible substrates to conform to the organ shape
- tactile, temperature, and other sensors embedded to surgical instruments of varying shapes for minimally invasive surgery

Logistics enabling applications
- RFID tags with unfoldable antennas

Paper-embedded wireless ID tags
- Paper tickets

Distributed Input devices
- pressure sensing in varying shape surfaces
- new touch interfaces

Sensitive skin
- sensor arrays that can be placed onto non-planar surfaces of robots for increased perception
- inexpensive upgrades that adapt to existing surfaces without major structural alterations
- constant monitoring micro sensors for structural integrity of wide surfaces
- skins incorporating arrays of shear-stress sensors

Foil with Solar cells
- Larger area solar cells

1.3 Goal and challenges

The goal of the present research is to create wafer level flexible and stretchable electronic substrates, where both the electronics and the interconnections are flexible. Deformable electronics could be realized by lateral partitioning of the (thinned) silicon substrate on sub-millimetre scale (see Fig. 1.1). By varying the segment dimensions and the geometry of
interconnecting bridges, a level of acceptable deformations can be reached. In practical realization such ultra thin silicon segments and their interconnection structures have to be protected by a polymer or silicone rubber film.

![Diagram of thinned and partitioned silicon segments and their interconnections.](image)

Fig. 1.1 Concept of thinned and partitioned silicon segments and their interconnections.

The technologies for creating these ultra-thin flexible and stretchable electronic substrates include fabrication of silicon segments including active electronics, formation of flexible or stretchable interconnections between the segments and embedment or sandwiching of the structure into a soft material. In this project, a thin polysilicon layer is used as a replacement for the more expensive SOI (Silicon On Insulator) wafer at the initial stages of the process development. For interconnection of the segments various technologies can be applied such as wire bonding, conductive glue, metal evaporation, sputtering or electroplating. The latter three options were chosen because of the fact that they suit well the CMOS technology that was used for the formation of the segmented silicon structures.

The design of the system of segments with interconnections being embedded in a soft material has to be accompanied with dedicated design simulations in order to realise an optimal system for stretchability, flexibility and reliability. The creation of appropriate simulation models is also a challenging task because of the differences in scales within the product. Here it should be noted that flexible and stretchable substrates with a sufficient mechanical reliability for stretching as well as bending are new topic. The suitability of the simulation models as well as the failure criteria should be tested by performing reliability measurements. For these it turned out that a displacement controlled test facility with sufficient accuracy was unavailable. Therefore it was decided to build a new test facility. With this also the observation of damage with the aid of a microscope could well be realized.
However, this research work is not isolated. Two other closely related research projects namely PACD B3 and BSIK III-B-5a were started at Delft University of Technology lately. In the PACD B3 project the wafer-level fabrication technology for flexible and stretchable silicon electronics is investigated. In the BSIK project wafer-level fabrication modules for achieving high-level of stretchability are studied. While both these projects focus on fabrication issues, in this project focus is on the structural design including segment and interconnection geometry, mechanical characterization of samples, FE simulations, material characterization and modeling. During the course of these projects fruitful mutual collaboration has developed in the form of test sample fabrication on one side and feedback from sample characterization and FE modeling on optimization on other side.

1.4 The objectives of the thesis

The aim of this work is to develop and verify a concept of flexible and stretchable substrates that can be created through CMOS technology. Therefore, the major objectives of this thesis are:

- Design of flexible and stretchable substrates with embedded or sandwiched silicon segments (within polymer) of various geometries.
- Design of suitable interconnections between the segments, embedded or sandwiched into polymer.
- Design and fabricate dedicated mechanical characterization methods for the ultra-thin substrates for both stretching and bending.
- Detection of cracking (and/or delamination) in the substrates and of damage in the interconnections.
- Investigation of the failures of the flexible and stretchable substrates and comparison with FE modeling results.
- Mechanical characterization and modeling of the constitutive behavior of the polymer materials used (including silicone rubber). The models are used for the FE simulations.

1.5 Outline of the thesis

This thesis starts in Chapter 1 with a brief introduction to the topic of flexible and stretchable substrates and defines the thesis framework and goals. In Chapter 2, a concept to create a
flexible and stretchable substrate on the basis of CMOS processing is worked out based on the technology of silicon on anything [Dekker, 2003]. The idea is to create small thin silicon based electronic segments that are embedded in a stretchable and flexible polymer material. Based on this idea, a preliminary design is first discussed. Here square and hexagonal segments are selected for actual fabrication. The primary objective was developing a suitable concept of designing, fabrication and testing. This concept is actually worked out and the substrates being obtained are verified with respect to suitability concerning fabrication, stretchability and flexibility.

For the verification of the stretchability and flexibility bending and tensile test setups were designed and fabricated. Here displacement control of the sample loading turned out to be important. Further, for the observation of damage initiation and evolution an optical microscope combined with digital image processing was used. As the substrates are extremely flexible, normal bending tests that are generally used for testing the behavior of beam structures could not be used. Therefore, for testing the suitability of the substrates to withstand bending deformation in the newly designed test setup the substrate is being wrapped around a cylinder of chosen (small) diameter. In order to gain more insight in the occurrence and evolution of damage both the bending and tensile experiments are accompanied by FE calculations. From the testing and further analyses of the damage phenomena of the 1st generation samples we learned that very early damage occurred in the dielectric layers that remained on the polymer in between the segments as a result of the chosen fabrication process.

Because of the early damage initiation found for the 1st generation samples, in Chapter 3 a modified design was proposed and worked out. In this design of the so-called 2nd generation flexible and stretchable substrates, the dielectric layers in between the segments were omitted. For this purpose not only the silicon layer but also all dielectric layers are segmented. The mechanical behaviour of these 2nd generation samples was explored and the experimental results and the supporting FE simulations are discussed.

In the 1st generation sample design, for simplicity reasons, there were no interconnections between the segments. For the 2nd generation test structures various interconnection types were included. In order to test the reliability of these interconnect structures, the electrical resistances were measured during the tensile and bending tests. For this purpose the test setups were extended with a possibility to perform resistance measurements during deformation. The occurrence of failure (crack occurrence and/or drop in resistance) in the segments and/or the
interconnections during stretching and/or bending is taken as a measure of the (un-)suitability of the design variants for practical application. More insight into the occurrence of failure of the interconnections was gained by FE mechanical simulation results. FE simulations were also performed for various alternative interconnection shapes. Geometry parameter sensitivities with respect to the maximum stress level in the interconnections were established. However, a good correlation between maximum stress level and electrical resistance could not be established.

From the experiments and the FE simulations for the 2nd generation samples it was concluded that insufficient flexibility is obtained for the considered interconnection shapes. It is believed that this is caused by the embedding of the segments and interconnections within the polyimide. Because of this embedment the mechanical “spring behavior” of the interconnections appears to be very restricted. For this reason in Chapter 4 the concept of “Future Flexible and Stretchable Substrate I” with embedding in a much softer material (silicone rubber) is first worked out. Next, in Chapter 5, the concept of “Future Flexible and Stretchable Substrate II” with complete free-standing interconnection (not embedded) is considered. The latter resulted in a new concept of “future flexible and stretchable substrates”, where silicon segments with “free standing interconnections” are sandwiched in between silicone rubber sheets. Both the concept with embedment in silicone rubber and sandwiching between silicone rubber sheets were explored through FE simulations only. The actual realization and testing should be performed in a future continuation of the project.

For the FE simulations of the concept with embedment within silicone rubber (see Chapter 4) a dedicated rubbery elastic constitutive model should be available. Therefore, various mechanical tests were carried out on silicone rubber foil. Among these are cyclic deformation tests, tensile tests (until rupture) and double shear tests. The analysis of visco-elastic properties by (small strain) Dynamic Mechanical Analysis (DMA) was performed to establish the glass transition temperature. On the basis of the DMA data it is concluded that at room temperature the silicone rubber really behaves elastic. The rubbery elastic model is presented in section 4.2.3. The FE simulations were performed in order to explore the possible improvement in mechanical behaviour of the substrates by using silicone rubber instead of polyimide as encapsulating material, but now using the established rubbery constitutive model.

Based on the FE simulation results, first the Si support structure will fail and subsequently the rubber will fail when increasing the mean sample strain. Failure of the Si-segments is likely not to occur at all. Compared to the 2nd generation, the “Future Flexible and Stretchable
Substrate I” only gives an improvement of about a factor 2 for the mean strain level. The limiting factor for the improvement is the disappointing behavior of the Si-support structure. Apparently, the embedment of the Si-support structure by rubber very much reduces the “spring behavior” of the sinusoidal support structure. Therefore, in the next Chapter a “Future Flexible and Stretchable Substrate II” is suggested, where not complete embedment by silicone rubber is used, but only sandwiching the spring structure between two silicone rubber foils is proposed.

Chapter 5 presents the concept of interconnection using a completely free-standing interconnection (not embedded) between the segments. Without the embedment in a protecting material, the mechanical “spring behavior” of the interconnection is fully available. Also the interconnection material was replaced. Because of the better electrical and mechanical performance copper interconnections are chosen here. Interconnections of various shapes were explored while changing various geometric parameters. Compared to the FE results for the previous concepts it is found that for the free standing interconnects (sandwiched between silicone rubber sheets for protection against over stretching and against environmental influences) an enormous improvement of the stretchability is found. For the most favourable case the established equivalent strain for a mean elongation of 176% (which is the limit for the silicone rubber sheets) is found to be 0.64% only. This is below the elastic strain limit of the Copper. As a result, the interconnection will behave fully elastic and thus will not be damaged, even not under cyclic elongation.

Finally, in Chapter 6, the thesis is concluded with a review of the research being reported. Recommendations for the design of a most promising flexible and stretchable substrate design are given. The actual fabrication and testing of this “future design” should be performed in a future continuation project.
References


STELLA project website: http://www.stella-project.de/

SWEET project website: http://tfcg.elis.ugent.be/projects/sweet/Welcome.html


2.1 Introduction

A silicon wafer can be made flexible to a certain extent by its thinning. It was shown that after thinning to a thickness of about 50 μm or less [Erik Jung, et al., (2001)], the wafer can be subjected to moderate in-extensional bending. As discussed before, the purpose of the present research is to develop a microelectronic substrate that not just allows in-extensional bending, but can be bent to an arbitrary curved surface. This requires stretchability and flexibility at the same time. As a starting point in achieving this goal, the substrate transfer technology for SOI and non-SOI single-crystalline silicon wafers developed at Philips [Dekker, 2003] was adapted and tested for its flexibility and stretchability limits. In this technology optimized for high-performance low-power RF applications, the bulk silicon substrate is removed and only the very thin top silicon layer with active devices is transferred onto a glass carrier having low dielectric losses. As a variation of this process, the active silicon layer including interconnects can also be transferred onto a thin (5-10 μm) polyimide film resulting in a fully functional ultra-thin single-crystalline silicon integrated circuits. In the original work a high-level of flexibility was demonstrated but without enough quantitative analysis.

In this chapter, a first idea to form a flexible and stretchable substrate is worked out. The idea is to create small thin silicon electronic segments that are embedded in a flexible polymer
material. The electronic segments should be electrically connected through flexible connections that will be developed separately (see Chapter 3).

The present chapter discusses a preliminary design and the related fabrication process. An adapted version of the above mentioned substrate transfer technology is used. It allows partitioning of the silicon layer into segments, but it uses continuous dielectric layers e.g. silicon oxide layer. Proper geometries of segments are selected, such that regular microelectronics patterning methods still can be used and the strain concentrations in the substrate under the required loading remains within acceptable limits. Among various possibilities, square and hexagon segments are chosen in this preliminary design.

The primary objective of the preliminary design is verification of the suitability of the concept, concerning fabrication, stretchability, flexibility and the occurrence of failure during loading. In order to investigate the effect of segment size and gap size on the occurrence of failure during stretching and bending, several design variants with different combinations of segment size and gap size are considered. In particular the occurrence of damage during stretching and bending tests is taken as a measure of the suitability of the design variants for practical applications.

The qualification testing of the flexible and stretchable substrate samples is challenging because standard bending tests can not be executed because of high sample flexibility. Therefore custom designed bending and tensile test setups were fabricated. Observation of damage evolution is performed through optical microscopy combined with digital image processing.

In order to get better understanding of the occurrence of (first) damage, the stress/strain development during the bending and tensile tests is simulated through FEM calculations. Here global-local modeling is employed because of the extreme aspect ratio’s present in the substrates.

### 2.2 Design and fabrication

#### 2.2.1 Design

Various segment geometries could be chosen. Among the various possibilities circular or other elliptical geometries will have the advantage that no stress singularities are expected on the interface between silicon and embedding polymer. However, when the area of silicon available for active electronics needs to be maximized, square or hexagonal segments are preferred. These are also more convenient from the perspective of layout design. Therefore square and hexagonal
geometry of segments was selected for the initial experiments. The actual design of interconnections (see Chapters 3, 5) was performed for the concept with square islands only. However, since the connections are realized between two parallel segment borders, they will also be applicable to parallel borders of the hexagonal segments. Also, in the preliminary design no electronics was fabricated on the silicon islands.

Fig. 2.1. Schematics of the sample with hexagonal segments

Fig. 2.2. Schematics of the sample with square segments
In order to investigate the effect of segment size and gap size (between the segments) on the occurrence of failure during stretching and bending of the structure, samples were designed with square and hexagonal partitions varying in segment size from 2000 µm to 150 µm and in gap size from 250 µm and 20 µm. The following table shows the details.

<table>
<thead>
<tr>
<th>sample</th>
<th>segment side length (µm)</th>
<th>gap size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>600</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>250</td>
</tr>
</tbody>
</table>

### 2.2.2 Process and fabrication

For the preliminary design the square and hexagonal samples should be embedded in a flexible and stretchable polymer. For the polymer it was decided to use a polyimide. A photolithography process was performed to transfer patterns of the segment’s geometric shapes (squares and hexagons) on a mask to a thin layer of photosensitive material (photoresist) covering the surface of the polysilicon substrate. The photolithography technology typically includes 4 steps: photoresist coating by spinning the substrates at high speed, exposure causing the chemical change in the photoresist, development and hardbaking. The segmented silicon substrate was then transferred onto a thin polyimide layer using substrate transfer technology. This structure was subsequently adhesively bonded to a temporary glass carrier using acrylic glue to hold the structure conveniently during grinding of the silicon wafer. Prior to bonding, a adhesion promoter was applied at the wafer edge. After removal of bulk silicon by wet etching, the segmented “ultra-thin silicon segments on a PI substrate” samples were pealed off from the temporary glass carrier and were ready for characterization.

The 1st generation sample fabrication procedure is subsequently discussed step by step, as illustrated in Figs 2.3, 2.4 and 2.5.
Step 1: The sample preparation started on 4” p-type silicon wafers. A 300nm thermal oxide layer was deposited on the top surface of the silicon wafer to be used as an etch-stop layer in a later process step (step 17).

Step 2: A 500nm poly-silicon layer was deposited by LPCVD (Low Pressure Chemical Vapor Deposition) on the silicon oxide layer which was fabricated in step 1. This thin polysilicon (step 2) and silicon oxide (step 1) layer were used as a replacement for more expensive SOI (Silicon On Insulator) wafer at the initial stages of the process development. At the final stages of development SOI wafers can be used to integrate sensors and/or electronics if required.

Step 3: A coating process was performed by spinning the substrates at high speed to coat a positive photoresist layer on the poly-silicon layer for the pattern transfer process steps later.

Step 4: The mask specially designed and fabricated with the test structures layout (i.e. square and hexagonal segmentation) was put above the photo-resist with a few microns gap. The photoresist was then exposed under UV light.

Step 5: Once exposed, the substrate was subsequently immersed in a TMAH based photoresist developer solution. Developer solutions dissolved away areas of the photoresist that were exposed to light. Therefore, after successful development, the photoresist was patterned with the mask image that was provided. After development, a post baking at 115°C for 1 minute was performed. This was needed to drive off remaining solvants and to crosslink the remaining photoresist. Cross-linking the polymer increases mechanical and chemical stability of the material.

Step 6: The polysilicon that is not covered by photoresist coating was removed by chlorine plasma etching.

Step 7: Square or hexagon polysilicon segments are retained after removing the remaining photoresist by oxygen plasma etching.

Step 8: A 500nm thick PECVD (Plasma Enhanced Chemical Vapor Deposition) oxide layer was deposited on the structure.
Step 9: An about 8-9 $\mu$m-thick layer of photosensitive Durimide™ polyimide was spin coated on the segmented ultra thin polysilicon substrate. Subsequently, the polyimide was backed at 120$^\circ$C for a few minutes to be partly cured.

Step 10: A photoresist layer of about 2 $\mu$m was coated by spinning. A mask specially designed and fabricated with the whole area covered, except the borders of 10mm, was put above
the photo-resist with a few microns gap. The photoresist was then exposed under UV light.

Step 11: A TMAH based positive photoresist developer was used to develop photoresist. Developer solutions dissolved away the areas of the photoresist that were exposed to light and the areas of polyimide below the exposed photoresist in the same step. In this manner the photoresist and polyimide on 10 mm from the edge were removed. (After this step a polyimide border of several mm is always retained)

Step 12: The photo-resist layer was removed.

The final polymerization of polyimide took place at about 300°C for 1 hour in nitrogen environment.

Step 13: A 300nm thick PECVD (Plasma Enhanced Chemical Vapor Deposition) oxide layer was coated on the polyimide. This is done in order to weaken the contact strength between the substrate and the glue (that is applied in step 15).

Step 14: A primer layer of diluted silane (A174) adhesion promoter was coated on the (10 mm) edge of the wafer. The primer will locally strengthen the interface between the silicon oxide and the glue (that is applied in step 15).
Step 15: A glass substrate (AF45 type from Schoot) was bonded to the Si-oxide layer with UV-sensitive acrylic glue. The gluing procedure was similar to the SOA (Silicon On Anything) process [R. Dekker, et al., (2003)].

Step 16: The silicon was lapped down to about 50 µm thickness.

Step 17: The remaining silicon was removed in 33% 80°C KOH solution. The thermal oxide layer (deposited in step 1) was used as an etch stop.
Step 18: Finally, the samples were peeled off the glass substrate and were ready for characterization.

2.2.3 Flexible and stretchable samples

The fabricated samples consist of a 0.8 μm thick silicon layer sandwiched between a 300 nm thermal silicon dioxide layer (oxide layer 1 in Fig. 2.6) and a 500 nm PECVD silicon dioxide layer (oxide layer 2 in Fig. 2.6) with square or hexagonal segments varying in size from 150 to 2000 μm, embedded in polyimide. A 3rd silicon oxide layer is covering the bottom of the polyimide layer (oxide layer 3 in Fig. 2.6). Fig. 2.7 represents typical photos of samples.

Fig. 2.6 Schematics of sample cross-section

Fig. 2.7 Photographs of square and hexagon segmented samples

Fig. 2.8 shows the peeling off a sample from the glass carrier (step17). The pealed off samples are warped as a consequence of residual stress being built up during the fabrication
process. In order to avoid damage of the sample, a peeling tool was designed and fabricated (Fig. 2.9). The sample can be peeled off from the glass carrier by connecting a border of the sample to a cylinder with large diameter (by gluing or by applying adhesive tape) and subsequently rolling off the cylinder.

Fig. 2.8 Pealing off the flexible samples from the glass carrier by hand

Fig. 2.9 A schematics of a peeling tool
2.3 Testing

2.3.1 Introduction

In order to establish the occurrence of failure due to bending or stretching of the substrate, various tests have to be carried out. Common 3-point and 4-point bending tests are not feasible for the flexible samples because these are too flexible to apply any lateral loading. A common tensile test could be used, provided that the setup should have a possibility of damage observation of the sample. Special tensile and bending test setups were designed and fabricated. With these setups the damage observation can be done by optical microscopy and image processing. In the bending test the substrate is wrapped around a glass cylinder under small tensile loading.

Although the ultimate goal of the flexible and stretchable substrate is to allow for doubly curved bending and stretching in arbitrary directions, the tests here are limited to bending and stretching of the sample substrates in a few main directions only.

In order to get a first idea about the deformability of the substrates, one-directional tensile and bending testing is applied. With these tests the influence of segment size and gap size on the flexibility and stretchability can well be explored. Since cracks would become invisible after releasing the loads (according to previous experience), direct optical observation during the loading procedure is crucial.

2.3.2 Test setup and test process

Tensile tests

The tensile tool includes clamps, a micro-screw loading part, a force sensor and a displacement sensor (see Fig. 2.10). The force and displacement data are recorded by use of a data acquisition system. An optical microscope with CCD-camera and computer is used for monitoring the crack initiation and crack evolution. The displacement is manually controlled for the convenience of stepwise loading and crack observation during the test. Tensile test results will be presented and discussed in section 2.3.4.
Bending tests

Since the usual 3-point and 4-point bending test are not feasible for the segmented thin flexible substrates because of the high flexibility, a special bending test tool was designed and fabricated (see Fig. 2.11). On this test tool the sample is bent around a test cylinder. By using test cylinders of various diameters the suitability of the substrate at bending deformation with various radii of curvature is tested. In order to be able to observe the occurrence of cracking during the tests, the test cylinders were made from glass, such that the lighting is easily transferred through the substrates. Because of the flexibility of the substrate and the warpage due to residual stress, it is necessary to mount the substrates on the test setup with a small tensile-load (0.1 N was selected). After that the substrate is wrapped around the (fixed) glass cylinder by moving down the two load cylinders (see Fig. 2.11). The microscope could be rotated perpendicular to the glass cylinder surfaces to observe and monitor possible cracks.
Fig. 2.11 Photograph and schematics of bending test setup

The samples are first wrapped around the glass cylinder having the largest diameter of 10 mm. Then the specimens are observed under the optical microscope during loading. When no crack is observed on the bent sample, the procedure is repeated with a glass cylinder of a smaller diameter. This is repeated with each time smaller diameters until finally a crack is observed. Fig. 2.12 shows the glass cylinders being used in this procedure. Bending test results will be presented and discussed in section 2.3.3.
2.3.3 Bending test results

The first crack appeared in a silicon oxide layer in-between the silicon segments. The crack propagated at higher loads within a silicon oxide layer on the segments (or possibly in the silicon segments) as it can be observed in Fig. 2.13. The cracks were more or less parallel with the axis of the bending cylinder. The ultra thin silicon segments are slightly transparent, thus cracks below the silicon segments (in the oxide) are also visible (See Fig 2.13a). No crack was observed in the first layer on top of the silicon segments. The above observations held for all the bending tests. In all cases the first crack initiated in the silicon dioxide layer between the silicon segments.

Fig. 2.14 shows for samples with square segments, that the diameters for which the first crack occurs depend on the ratio of “segment side length” to “gap size” as well as on the “segment side length”. Fig. 2.15 shows the same dependencies for samples with hexagonal segments. The bending diameters for the first crack occurrence increase with increasing segment size and with decreasing gap size between the segments. No crack was detected for the sample with square segments of 450 μm side length and 120 μm gap size and for the sample with hexagon segments of 300 μm side length and 40 μm gap size, even not for bending around a cylinder with the smallest diameter of 2 mm. So these are present with bending diameter 0mm in Fig. 2.14 and 2.15.
Fig. 2.13 Cracks on flexible sample with square and hexagonal pattern under bending tests
Fig. 2.14 Bending diameters for crack onset for samples with square segments
Fig. 2.15 Bending diameters for crack onset for samples with hexagon segments

2.3.4 Tensile test results

Just as was observed for the bending tests, the first cracks for the tensile tests also appear in the silicon oxide layer in-between segments. Fig. 2.16 shows that the directions of cracks are more or less perpendicular to the loading direction.
Fig. 2.16 Cracks of flexible sample with square and flexible patterns under tensile testing

The thickness of the segments is only about 500nm. Therefore the segments are slightly transparent. Consequently the cracks which are below segments are partly visible. Fig. 2.16 and Fig.17 show the shapes and the schematics of the first crack of the samples with hexagon segments under tensile testing. No skew crack was detected on the silicon segments, the first crack probably started in the oxide layers at the gap position and subsequently propagated into the oxide layers below and/or on top of the silicon and may be also within the silicon itself.
The “critical strain” can be defined as the mean strain where the first crack is observed. The first crack was detected at the early stage. Later cracks were observed in all silicon dioxide layers and silicon segments. From the following stress-strain curve (Fig. 2.19), it can be observed that the initial stiffness for all the samples is almost the same, the slopes change at about 0.8% strain because afterwards the cracks start to affect the samples’ stiffness. The results are consistent with the bending test results of just a polyimide layer with oxide layers, where a
maximum bending strain in the oxide at first cracking was established around 0.8%. The stiffness depends on the ratio “segment side length to gap” and the crack density.

The “critical strain” depends on not only the ratio of segment side length to gap size but also on the segment sizes and gap sizes itself. Figure 2.18 shows that no crack was detected for the samples with hexagon segment 450 µm and gap size 120 µm until the strain was up to 0.78%. This was more than observed in all other samples. The strains at first crack depend on the segment size and gap size. The larger the segment size is compared to the gap size, the less the strain at first cracking is. However, the sample with 150 µm hexagon segments do not observe this trend, the reason probably is the strain localization.

The “critical strain” for the sample with square segment 300 µm and gap size 40 µm reached 0.74%. Only this single square segment sample was tested under tensile loading, because it turned out that the substrate stretchability was quite disappointing because of the early failure of the continuous silicon oxide layer (see next section). Therefore it was decided to further focus on the second generation samples, where the continuous oxide layer was omitted.

Fig. 2.19 Mean Stress versus mean Strain curve for samples with and without hexagonal segments in tensile tests.

The diagram shows the stress (in MPa) versus strain (%) for various samples with different segment and gap sizes. The legend indicates that the samples are labeled as hexa150_20, Hexa300_40, hexa450_60, hexa450_120, hexa600_80, hexa2000_250, and oxide/pi layer. The strains at first crack depend on the segment size and gap size. The larger the segment size is compared to the gap size, the less the strain at first cracking is. However, the sample with 150 µm hexagon segments do not observe this trend, the reason probably is the strain localization.
2.3.5 Evolution of cracks

Evolution of cracks on thin silicon oxide substrate

Since all cracks initiated in the continuous silicon oxide layers at relatively low strain, it can be concluded that the presence of these layers seriously limits the flexibility and stretchability of the samples. It is widely recognized that ultra-thin silicon oxide is flexible under bending deformation. However, the silicon oxide properties were not yet explored in detail so far. Most investigations focus on the tensile properties of silicon oxide. We tried to investigate the growth of the number of cracks and the crack width in silicon oxide on a stretchable thin film under tensile or bending deformation.

The sample was made up by two 500 nm silicon oxide layers sandwiching the polyimide layer with 8 µm thickness, with a glue layer at the bottom. Fig. 2.20 shows the structure and bending direction schematics. The deformation images were digitally recorded and processed to analyze the crack number and crack width during the bending and tensile tests.

![Fig. 2.20 Schematic of ultra-thin oxide film Structure and bending direction.](image)

The first crack was detected when the sample was bent around the cylinder with diameter of 2 mm. The cracks were parallel with the axis of the bending cylinder. According to the relation between the curvature and the strain, the failure strain for the first crack should be approximately 0.8%.
Fig. 2.21  Tensile test for silicon oxide on polyimide structure.

From Fig. 2.21, we can see that the two tensile test curves match well within the strain range less than 1%. The first crack appeared at the strain of 0.77% and 0.9% for samples ‘tensile 1’ and ‘tensile 2,’ respectively, which is consistent with the result of the bending tests. The ‘tensile 1’ test was paused for 15 hours when the strain was up to 1.04%. The strain keeps constant while the stress decreases significantly because of the polyimide viscoelastic properties.

![Loading direction](image)

Fig. 2.22 The cracks on the silicon oxide under the tensile loading.

Fig. 2.22 shows the cracks on the silicon oxide layer under tensile loading. All the cracks are perpendicular to the loading direction. Images of cracked samples were recorded during loading for the tensile and bending tests as well. In particular the tensile test samples show a continuous
The evolution of crack width and number of cracks. The data was processed by image software to record the number of cracks and (average) crack width (see Figs. 2.23 and 2.24).

**Fig. 2.23** Average crack width of ultra-thin oxide film under tensile tests (results of test 2)

**Fig. 2.24** The number of cracks in the ultra-thin oxide film under tensile testing (results of test 2)

From Figs. 2.23 and 2.24, we can see that the crack density increases sharply with the strain at early stage and subsequently increases slightly. The crack width steadily increases until the sample breaks.
Evolution of cracks on the sample with segments

Occurrence of various cracks on hexagonal segments (and gaps between those segments) at a certain moment during tensile testing

Occurrence of various cracks on square segments (and gaps between those segments) at a certain moment during tensile testing

Fig. 2.25. Crack occurrence on segments and gaps at a certain moment during tensile testing
The cracks appear on the segments and the gaps between segments during the loading for samples with square and hexagonal segments. The crack shapes are not regular because of the complicated structure of the samples, the crack number increases continuously. The crack number and size are difficult to recognize because of the irregular shapes. The cracks go through the oxide layers on the segments and on the gaps between the segments. However, it might also be so that the silicon segments are cracked as well (see Fig. 2.25 a, b). The crack directions are almost perpendicular to the tensile loading direction. However, for samples with square segments, some cracks only go through the gaps between the segments. Probably, there occurs also interface delamination for the samples with the square segments.

2.3.6. Conclusion

For bending as well as for tensile loading the first crack appears on a silicon oxide layer in-between the segments. For samples with hexagonal segments, the first crack runs through the gaps and the segments as well. However, for samples with square segments the first cracks are found in the silicon oxide layers within the gaps only, because the strain localization in the relatively soft gaps. The development of first cracks depends significantly on the silicon segmentation size and gap size.

There is no crack detected under bending on glass rods with 2 mm diameter for samples with square segments with 450 μm side length and 120 μm gap size. The same holds for samples with hexagonal segments with 300 μm side length and 40 μm gap size. It can be concluded that these substrates are applicable on (single curved) surfaces with radii of 1 mm and larger.

The crack density increased sharply with the strain at early stage and then increased slightly. The crack width increased steadily with loading for all substrates being tested. The cracks go through the oxide layers on the segments and on the gaps between the segments. It might also be so that the silicon segments are cracked as well, although that could not be proven. All cracks are more or less perpendicular to the tensile loading direction.
2.4 Simulations of flexible substrate behaviour

2.4.1 Introduction

In order to get more insight in the occurrence of fabrication and testing induced failures (testing under bending and/or stretching) various FEM simulations of process steps and subsequent testing conditions were performed. Originally simulation based optimization of the system was planned, to finally attain a robust substrate that can withstand relatively highest combinations of stretching and bending, without loosing functionality.

The FE simulations were performed parallel to the substrate testing in order get more understanding in the occurrence of failure.

For the simulations adequate material parameters are necessary. The large ratio of width (or length) to thickness offered a challenge to reliable FE simulation. Therefore multilevel FEM simulations were performed. A global-local model has the advantage of subdividing large models into multiple, moderate-size models and thus also separating fixed model parts from parts of the model that may undergo design changes [MSC. Marc, 2003].

Tensile and bending simulations are performed to understand the failure causes. From comparison to the experimental results we learned that the simulations provide good insight into possible places of crack initiation while the ultimate mean strains matched well.

2.4.2 Material properties

The poly-silicon and silicon oxide are regarded as elastic materials. Actually, polyimide is a viscoelastic material. It behaves slightly time and temperature dependent. However, the material behaviour at room temperature (far below the glass transition temperature, Tg~371°C) can be considered elastic for the quasi-static short duration loading. Therefore in the present tensile and bending simulations only linear elastic properties were taken into account. The following table shows the material property data in detail.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymide</td>
<td>3</td>
<td>0.30</td>
</tr>
<tr>
<td>Poly-silicon</td>
<td>169</td>
<td>0.27</td>
</tr>
<tr>
<td>Silicon oxide</td>
<td>75</td>
<td>0.3</td>
</tr>
</tbody>
</table>
2.4.3 Simulations

Global-local FEM modelling simulations were employed to adequately cope with the large width (or length) to thickness ratio. In this method, the sample with segments is modelled as a global model with a relatively coarse mesh, which is just used to capture the overall deformation of the flexible sample under the applied loading. In the global model a small area, being a so-called “representative unit cell” is surrounded by a continuum with “equivalent mechanical properties” as illustrated in Fig. 2.26.

![Unit cell surrounded by continuum with “Equivalent” mechanical properties](image)

**Fig. 2.26** Unit cell surrounded by continuum with “Equivalent” mechanical properties

The unit cells selected are made up from a silicon segment in the centre, surrounded by gap materials plus some parts of the surrounding segments as well. See the illustration in Fig. 2.27. The unit cells are discretized (as local models) with a fine mesh to well capture the details. These local models were finally applied for accurate local stress-strain investigation, where the
global simulation results at the boundaries were applied as boundary conditions. But they were first used to establish the “equivalent” mechanical properties as used in the global model. The procedure to attain the “equivalent” mechanical properties is described in Appendix A. The global-local models were created with Marc software using mechanical 3-D solid elements type 7 (Type 7 is an eight-node, hexahedral element with eight-point Gaussian integration).

In the global bending and tensile simulation models, the substrates (both hexagonal and square case) were modelled with a relatively coarse mesh, for the “equivalent” material area as well as for the unit cell area.

**Bending case**

In the bending modelling, the (bottom) surfaces of the lower elements of the flexible samples are bent over the rigid cylindrical surface of the glass rods. The cylindrical glass rods are modelled as rigid bodies. Within the MARC program the contact of nodal points to the rigid body is tested during the simulation. No load transmission by shear stress is assumed on the contact surface. This assumption was done because of the low normal forces expected on the contact surface. The surface of the cylindrical rod is described as an analytical entity because this is more accurate than a piecewise approximation of curved element boundaries. Global-local bending simulations were performed for the various cylinder radii as used in the experiments.

![Fig. 2.27. Schematics of contact bending model](image)
Fig. 2.28  Simulated principle max local strain on the first silicon oxide layer when bending around cylinders with various diameters for samples with square segments.

Fig. 2.29  Simulated principle max local strain on the first silicon oxide layer when bending around cylinders with various diameters for samples with hexagonal segments.

The curves of max principle strain on the first layer of silicon oxide versus bending diameter are showed in the above diagrams for samples with different segment- and gap sizes. The maximum principle strains decrease with the cylinder diameter for each sample and depend...
significantly on the segment sizes and gaps between the segments. The dotted line shows the silicon oxide’s “failure criterion” strain. For the data points (in Fig.2.28 and Fig.2.29) above this line the samples probably will be cracked. The samples with the largest segment size (2000 μm) were most critical in the bending tests.

![Bending curve around the cylindrical surface](image)

**Fig 3.30. Bending curve around the cylindrical surface**

Fig 3.30 shows the contact curve for the sample with large segments bending around the cylindrical rods. The sample can not locally bend around the cylindrical surface. Therefore more severe cases are expected for combinations of higher tensile loading and bending.

The max principal strain in the sample with segments with side length 450 μm and gap size 120 μm under the bending load with 2 mm cylinder diameter is below the critical strain. This matches well with the experimental results. The simulation results suggest that for samples with square segments with size 2000 μm and size 600 μm high flexibility could not be attained. Decreasing the segment size and increasing the gap between the segments have positive influence on the flexibility.

**Tensile case**

The tensile global-local models simulated the samples under a certain mean tensile strain level. The maximum stresses or maximum strains on the silicon segments and the silicon oxide layers under the applied mean tensile strain are thus established. Comparing the established maximum strains with the failure strains (for Si or Si-O) makes it possible to find the mean strain levels at onset of cracking. These values are presented in Figs. 2.31 and 2.32, together with the values as established from the experiments.
Fig. 2.31  The mean strain at crack onset as found from simulations and from experiments for the samples with hexagonal segments.

The simulated critical (mean) strains agree well with the mean tensile strain both for the samples with hexagon segments as well as for samples with square segments.
The maximum local principal strains appeared in the oxide layers within the gap between the silicon segments, near the spot where first fracture occurred during testing. As discussed before, from this spot they subsequently propagated into the oxide layers below and on top of the silicon and most probably also within the silicon itself. Simulation of crack propagation was not considered.

The simulation results matched the experimental results quite well in the level of mean critical strain as well as concerning the spot where the maximum local principle strain firstly reached the failure strain.

From the tensile testing as well from the simulation results we learned that fracture of the oxide layers limit the stretchability of the substrates severely. Therefore we decided not to perform simulation based optimization for these substrate types. Instead, we directly started to design the 2nd generation samples where the oxide layers in the gaps were omitted.

2.5 Conclusion

A promising concept for the realization of flexible and stretchable substrates was discussed. Part of the concept is the transfer of thinned and lateral partitioned silicon (segments). For the present research on flexibility and stretchability the transferred silicon segments are replaced by polysilicon segments for the reason of cost reduction. Both the original fabrication steps and the “replacement fabrication steps” are discussed.
In order to investigate the effect of segment size and gap size on the occurrence of failure under bending and stretching, test samples were designed and prepared. The test samples being considered have hexagon or square partitions varying in size from 150 to 2000 μm. The occurrence of failure is limited the applicability of the substrates. Special tensile and bending tools were fabricated to in situ observe the occurrence of cracks during loading. An optical microscope with the possibility of recording and analysing the digital images is used for establishing the crack density and width.

The (tensile-) failure strain of silicon oxide established on a layer of 500 nm thickness is about 0.8%. The same failure (principal) strain was found in the bending tests on the substrates. The crack density appears to increase rapidly at early stage of loading and subsequently increases slightly. However, the width of the cracks appears to increase steadily during loading.

Experimental and simulation results for the onset of cracking are consistent. It is shown that the first cracks appear in the oxide layers in the gaps between the silicon segments. Only at higher (mean) deformations they propagate or are generated within the silicon itself. The onset of cracking depends significantly on the silicon segmentation size. The segment size and gap size also affects the crack density and the crack width at larger (mean) deformation.

There is no crack detected under bending around the glass rods with the smallest diameter (Φ= 2 mm) for samples with square segments with 450 μm side length and 120 μm gap size and with hexagonal segments with 300 μm side length and 40 μm gap size. The remaining bending results show that for other samples with square segments failure always occurs for bending around glass rods with the smallest diameter (Φ= 2 mm).

From the tensile testing as well from the simulation results we learned that occurrence of cracks in the oxide layers severely limit the stretchability of the substrates. Therefore we decided not to perform simulation based optimization for the 1st generation substrates. Instead, we directly started to design the 2nd generation samples where the oxide layers in the gaps were omitted (See Chapter 3).
References


MSC. Marc, Theory and User Information, 2003, pp. 4-26
3.1 Introduction

The concept of a flexible and stretchable substrate where thin silicon segments are embedded into a polyimide layer was discussed in the previous chapter. The mechanical behavior appeared to be somewhat disappointing as the experimental and FE simulation results demonstrate the occurrence of cracks at early stage of deformation, depending on the segment size and gap size. To increase the mechanical reliability a 2nd generation sample was designed. Here not only the silicon layer but also all brittle dielectric layers are segmented. The mechanical behaviour of these 2nd generation samples was extensively explored and the experimental results and the supporting FE simulations are discussed in this Chapter.

In the 1st generation sample design, for simplicity reason, there was no interconnection between the segments. In the present the 2nd generation test structures various interconnection types were included. In order to be able to verify the integrity of the conductive paths during mechanical loading, metal layer test structures (of aluminium) are now integrated on the poly-silicon segments as well as on poly-silicon support structures bridging the gaps. The reason that we have chosen to use poly-silicon support structures is discussed in section 3.2.2. The shape of the poly-silicon support structures with metallization on top was chosen more or less sinusoidal (the definition is given later). In this way flexible interconnects were designed for signal communication between the silicon segments, which in future can be used to implement
electrical functionalities. Just as for the 1\textsuperscript{st} generation samples, the poly-silicon parts are embedded in (flexible) polyimide.

In order to test the reliability of the interconnect structures, the electrical resistances were measured during the tensile and bending tests using specially designed and fabricated test tools where at the same time crack observation as previously discussed (see chapter 2) could be performed. The occurrence of failure (crack occurrence and/or drop in electrical resistance) in the segments and/or the interconnections during stretching and/or bending is taken as a measure of the suitability of the design variants for practical application.

Insight into the occurrence of failure of interconnections was gained by FE simulation results using Finite Element global-local models. FE simulations were also performed for alternative shapes of the interconnects. Some parameter sensitivities were established, but a complete parameter optimization was not performed because from the results it became clear that again insufficient flexibility was obtained for all considered interconnection shapes. It was believed that this is caused by the embedding of the interconnections within the polyimide. Based on the gained insight some modifications are proposed for “future generation” flexible and stretchable” substrates in Chapter 4.

\section*{3.2 Design and fabrication}

\subsection*{3.2.1 Design}

Because of the time constraints on the project, for the 2\textsuperscript{nd} generation samples it was decided to consider designs with square segments and interconnects only. Because it can be expected that the mechanical behaviour of small size segments embedded in polyimide will be better than that of large size segments, it was decided to drop the segment sizes 2000 \(\mu\text{m}\) and 600\(\mu\text{m}\) (as previously used for the 1\textsuperscript{st} generation samples). Also, compared to the 1\textsuperscript{st} generation samples other types of failure are to be expected. For the 1\textsuperscript{st} generation samples primarily we had to do with early crack initiation in the dielectric layers at the gap positions. Now that we omit the dielectric layers at the gap positions, this type of failure is not an issue any more. Instead, we now expect corner delamination between the segments and the (soft) polyimide or delamination between the interconnect structures and the (soft) polyimide. Further, electrical failure can be expected because of extensive deformation or cracking in the metallization on the interconnects. In order to reduce the probability to get corner delamination, we also included segments with rounded corners.
The layout for a single wafer (of 4 inch diameter) was chosen such that 20 samples with dimensions of 5.6 mm by 30 mm are positioned. These samples can have varying segment size (from 150 to 450 μm) and varying segment spacing (from 20 to 200 μm) (see table 3.1). As said, both segments with round corners and sharp corners were designed.

Table 3.1: Segment sizes and gap sizes for square segments and interconnection data

<table>
<thead>
<tr>
<th>Segment side length (μm)</th>
<th>Gap size (μm)</th>
<th>Number of half waves of interconnect</th>
<th>Half wave length (μm)</th>
<th>Wave amplitude (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>20</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>40</td>
<td>2</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>150</td>
<td>60</td>
<td>2</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>300</td>
<td>20</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>300</td>
<td>40</td>
<td>2</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>300</td>
<td>60</td>
<td>2</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>450</td>
<td>40</td>
<td>2</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>450</td>
<td>60</td>
<td>2</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td>450</td>
<td>120</td>
<td>2 or 6</td>
<td>36 or 19</td>
<td>48 or 46</td>
</tr>
<tr>
<td>450</td>
<td>200</td>
<td>2 or 6</td>
<td>76 or 31</td>
<td>55 or 46</td>
</tr>
</tbody>
</table>

The interconnection illustrations are given in Fig. 3.3. Various (more or less) sinusoidal interconnections were chosen, while varying the number of half waves, the (half) wave length and the wave amplitude (see Table 3.1). “More or less” sinusoidal means here that a sinus curve is connected to a straight line using a certain fillet radius (see Table 3.1). In the actual definition of the interconnections for the mask fabrication, the curves were replaced by a b-spline approximation. The electric interconnections between the individual silicon islands should provide mechanical and electrical reliability under the mechanical loads such as bending, stretching, etc. Fig. 3.1 gives an illustration of the concept of the interconnections between the square segments.
In order to verify the electrical integrity of the interconnections during mechanical loading, daisy chain conductive paths coupling the various segments are created. Here two testing paths were designed (see Fig. 3.2). The first one spans the sample from one side to the opposite in a straight line while the second includes interconnects in orthogonal directions as well. Bond pads for accessing the test structures were positioned at two opposite edges of the samples. The second path gives the possibility to evaluate the integrity of interconnects directed perpendicularly to the loading axis. The width of the metallization on the poly-silicon support structures between the poly-silicon segments is 2 μm. On top of the silicon segments the width of the metallization is chosen much larger in order to limit the overall path resistivity.
Fig. 3.2. Signal paths: (1) straight path, vertical interconnections; (2) orthogonal path, horizontal and vertical interconnections

The wave-shapes of interconnections were designed to accommodate relatively large overall deformations without getting high strain localizations in the interconnects. The chosen geometric parameters of the curved interconnects (see Table 3.1) are more or less arbitrarily chosen. They did not follow from an optimization procedure.
<table>
<thead>
<tr>
<th>Segment side length</th>
<th>Interconnection design</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>gap size: 20 μm</td>
</tr>
<tr>
<td></td>
<td>gap size: 40 μm</td>
</tr>
<tr>
<td></td>
<td>gap size: 60 μm</td>
</tr>
<tr>
<td>300</td>
<td>gap size: 20 μm</td>
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<tr>
<td></td>
<td>gap size: 40 μm</td>
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<tr>
<td></td>
<td>gap size: 60 μm</td>
</tr>
<tr>
<td>450</td>
<td>gap size: 40 μm</td>
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<tr>
<td></td>
<td>gap size: 120 μm</td>
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<td></td>
<td>gap size: 200 μm</td>
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<tr>
<td></td>
<td>gap size: 60 μm</td>
</tr>
<tr>
<td></td>
<td>gap size: 120 μm</td>
</tr>
<tr>
<td></td>
<td>gap size: 200 μm</td>
</tr>
</tbody>
</table>

Fig. 3.3 Illustration of metallization layouts. Measures according to Table 3.1
3.2.2 Process and fabrication

For the 2\textsuperscript{nd} generation sample design, the test structures are also embedded in the soft material polyimide like the 1\textsuperscript{st} generation samples. Like for the 1\textsuperscript{st} generation samples, the poly-silicon layer and the 1\textsuperscript{st} oxide layer are intended as a replacement for the silicon layer and oxide layer of the more expensive SOI wafer. In the final stages of development SOI wafers can be used to integrate sensors and/or electronics as required.

As said before, metal layer tests structures (of aluminium) are now integrated on the poly-silicon segments as well as on poly-silicon support structures bridging the gaps. This type of supported metallic interconnection was selected from a larger set of interconnection possibilities:

- The metallic interconnection lines could have been chosen without support, but in that case it is expected that they can be damaged by mechanical loading quite soon. Therefore a supported structure was chosen. Also the fabrication of metallic interconnections without a support structure would be complicated.
- Instead of using a poly silicon support also the use of a polyimide support for the metallic interconnection was among the possibilities. Because of fabrication complexity this idea was not worked out.
- Also the use of a wave structure in thickness direction (a 3D wave structure) was not considered for the same reason.
- Another promising way to make the electrical interconnection between the segments is by using conductive polymer based paste. We did not try this possibility because this method is not compatible with CMOS Technology.

In the sequence, the various process steps will be discussed. Compared to the process steps as discussed in section 2.2.2 “Process and fabrication for the 1\textsuperscript{st} generation samples”, here we have to do with the following differences:

- Two sets of bonding pads at the edges on samples are fabricated
- The support structures for the electrical interconnects are added
- The metallization is performed
- The silicon-oxide in the gaps is removed.

The 2\textsuperscript{nd} generation sample fabrication procedure is subsequently discussed step by step, as illustrated in Figs. 3.4 - 3.9.
Step 1: A 500 nm thermal oxide was grown on a 500-525 μm thick p-type wafer.

Step 2: A 500 nm thick low-stress LPCVD polycrystalline silicon layer was deposited on the silicon oxide layer (from step 1).

Step 3: A coating process was performed by spinning the substrates at high speed to coat a positive photoresist layer on the poly-silicon layer.

Step 4: The mask specially designed and fabricated to form two sets of windows at the edges of the final samples was put above the photo-resist with a few microns gap. The photoresist was exposed under UV light on an exposure tool ASMPAS 5000/50.

Step 5: After exposure, the substrate was subsequently immersed in a TMAH based photoresist developer solution. The developer solution dissolved away areas of the photoresist that were exposed to light. In this manner the photoresist was patterned with the mask image that was provided.

Step 6: The polysilicon that is not covered by photoresist coating was removed by chlorine plasma etching.

Step 7: Two sets of windows at the edges on the poly-silicon layer are retained by removing the remaining photoresist by oxygen plasma etching. These windows can provide access to the test structures after full processing and peeling-off the flexible foils.
Step 8: A 600 nm layer of aluminum (99%Al, 1%Si) was sputtered at 50°C on the poly-silicon layer.

Step 9: A coating process was performed by spinning the substrates at high speed to coat a positive photoresist layer on the aluminum layer.
Step 10: The mask was put above the photo-resist with a few microns gap. This mask contained the interconnections, bonding pads and the test structures on the segments. The photoresist was exposed under UV light on an exposure tool ASMPAS 5000/50.

Step 11: The substrate was subsequently immersed in a TMAH based photoresist developer solution after exposure. Developer solutions dissolved away areas of the photoresist that were exposed to light. In this manner the photoresist was patterned with the mask image that was provided.

Step 12: A plasma chemistry was used to etch the exposed aluminum layer (Cl2, Br2).

Step 13: After removing the remaining photoresist by oxygen plasma etching, the patterned aluminum layer was done, which contained the interconnections, bonding pads and the test structures on the segments.
Fig. 3.5 Process steps making the aluminium layer with the interconnections, bonding pads and the test structures on the segments

Step 14: After patterning the aluminum layer, a coating process was performed by spinning the substrates at high speed to coat a positive photoresist layer on the wafer.
Step 15: The mask was put above the photo-resist with a few microns gap. This mask defines the area of the poly-silicon islands and support under the metal wave-shape structures. The photoresist was exposed under UV light on an exposure tool ASMPAS 5000/50.

Step 16: The substrate was subsequently immersed in a TMAH based photoresist developer solution after exposure. Developer solutions dissolved away areas of the photoresist that were exposed to light. In this manner the photoresist was patterned with the mask image that was provided.

Step 17: The exposed poly-silicon is etched away using a plasma chemistry (SF$_6$, O$_2$) that does not attack aluminum.

Step 18: After removing the remaining photoresist by oxygen plasma etching, the patterned poly-silicon layer was done, which included square segments and supports under the metal wave-shape structures.

Fig. 3.6 Process steps to partition the poly-silicon layer into segments
Step 19: A 500 nm thick PECVD oxide was deposited on the structure.

Step 20: A coating process was performed by spinning the substrates at high speed to coat a positive photoresist layer on the wafer.

Step 21: The mask was put above the photo-resist with a few microns gap. The same mask as used for removing the silicon oxide between the segments. The photoresist was exposed under UV light on an exposure tool ASMPAS 5000/50.

Step 22: The substrate was subsequently immersed in a TMAH based photoresist developer solution after exposure. Developer solutions dissolved away areas of the photoresist that were exposed to light. In this manner the photoresist was patterned with the mask image that was provided.

Step 23: The exposed PECVD oxide is etched away using plasma chemistry.

Step 24: After removing the remaining photoresist by oxygen plasma etching, the patterned oxide layer was done, which only covered square segments.
Fig. 3.7 Process steps to remove the oxide between the segments

Step 25: A polyamic acid (Durimide\textsuperscript{TM}) was spun coated at 1000 rpm and soft baked at 120°C for 6 minutes.

Step 26: Before curing, the polyimide at the edge of the wafer was removed to withstand the KOH wet etching during the following steps (the same process step to remove the polyimide at the edge of wafer in chapter 2). The photoresist was patterned using an additional mask, only an outer ring (~5 mm) was exposed. The polyimide was
removed by developing for 7 minutes using a TMAOH based developer. The photoresist was removed with acetone. The patterned polyimide was cured for ~1 hour at 385°C in a N₂ environment. The cured polyimide had a thickness of 8-10 μm.

Step 27: On the cured polyimide layer, a 500 nm PECVD oxide layer was deposited at 300°C. Like the process for the 1st generation samples (Chapter 1), a primer layer of diluted silane (A174) adhesion promoter was coated on the edge of the wafer. The primer will locally strengthen the interface between the silicon oxide and the glue.

Step 28: At this stage the wafer was prepared for adhesive bonding to a temporary glass carrier. An acrylic glue with a UV-sensitive component was used to achieve the bonding. The glue was spun on the silicon wafer and then the glass wafer was placed on top of the glue. The silicon wafer-glue-glass sandwich was rotated at a high speed. After spinning, the glue was exposed under UV light for 5 minutes to cure the glue.

Fig. 3.8 Embedding of the segmented thin silicon substrate into polyimide and Transfer of the structure on a glass carrier
Step 29: The silicon substrate was etched for about 6 hours at 33% KOH at 85°C. The complete removal of the silicon substrate was finished at TMAOH at 85°C because of its increased selectivity towards the silicon oxide stop layer.

Step 30: The glass carrier wafer was diced in the dimensions of the test samples and after delamination of the polyimide foil (which contain the segments and wave-shape interconnections) from the glass carrier.

Step 31a: The silicon oxide layers from both sides were removed in a BHF 7:1( Buffered Hydrofluoric Acid) solution and the aluminum bond pads were exposed.

Step 31b: Intended wire bonding step:

Initially, each bond pad was designed to access the test channel by wire-bonding. However, the wire bonding turned out not to be possible for this sample because the polyimide behind the bond pad absorbed the bonding energy. Therefore it was decided to replace the wire bond connection by a connection using conductive paste.

Therefore the step 32 was added.

Step 32: A conductive paste was applied on the bond pads so that resistance could be tested using the loading setup developed for that purpose.

A disadvantage of the replacement of the wire bond connections by conductive past connections was that the size of the conductive past connections was that large that single bond pads could not be connected to single wires. As a result it was decided to connect all bond pads at one side of the sample to one single wire only. This was done for both sides of the sample. As a consequence the resistance of the individual circuits could not separately be measured anymore. Instead we measured the total resistance of the whole sample (with the individual circuits in parallel).
3.2.3 Flexible and stretchable samples

The fabricated samples consist of a 0.5 μm thick poly-silicon square segments varying in size from 150 to 450 μm, embedded in polyimide. Wave-shaped aluminium interconnections on poly-silicon support structures (of the same wave shape) bridge the poly-silicon segments. The width of the aluminium lines is 2 μm in the regions between the silicon segments. The width of the conductive path is much larger on top of the silicon segments to limit the overall path resistivity. Conductive paste balls on the bonding pads make the sample have access to resistance measurement during the tests. Fig. 3.10 and 3.11 show cross section schematics and typical photos of samples.
3.3 Testing

3.3.1 Introduction

In chapter 2, occurrence of cracks of the 1st generation flexible samples was investigated by tensile testing and bending around cylindrical rods. Since in the 2nd generation samples the (cracking) oxide layers are not present, this kind of failure under tensile or bending testing is not relevant anymore. Instead, delamination failures and/or failure of the interconnection lines are likely to occur. The latter type of failure is monitored by considering the increase of the electric resistance of the daisy chains. As said before, due to the fact that wire bonding was not possible, electrical conductive past had to be used. Actually, thin aluminium foils were now connected to
the pads by using the electrical conductive paste. As a consequence parallel daisy chains were measured together, and thus not the behaviour of a single daisy chain could be tested. Possible damage of the silicon segments and the interconnections is observed by optical microscope during the loading. In section 3.3.2 the tensile test setup and the tensile test results are discussed. In section 3.3.3 the bending test setup and the test results are considered.

3.3.2 Tensile tests

Tensile test setup

A specially designed tensile tool was used to test the 2nd generation flexible and stretchable samples. In the tensile test setup (see Fig. 3.12) both ends of the sample are clamped at the positions of the conductive past connections between the sample and the aluminium foil. Therefore the upper parts of the clamps are made from non-conductive material. The resistance change of the parallel daisy chains was measured during tensile loading. Images of the segments and interconnections were recorded with an optical microscope.

Fig. 3.12 Photographs of tensile test setup with resistance measurement
Tensile test results

The 1\textsuperscript{st} generation samples (segmented silicon + continuous dielectric layers) suffered from cracking initiated in the continuous oxide layers in between the segments and then propagated to the oxide layers on the silicon segments (and possibly also in the segments). The 2\textsuperscript{nd} generation samples (polysilicon as well as the oxide layers are segmented) are also tested under tensile loading. At each tensile step, the sample elongation, applied force, and electrical resistance were recorded. Snapshots of the sample were also taken at each loading step to link the crack onset to the specific loading condition. Fig. 3.13 illustrates a first crack on a segment under tensile load. In the 1\textsuperscript{st} generation samples (Chapter 2), the cracks evolve through multiple segments after the initial crack on the silicon oxide on the area between the segments. However, in the fully segmented structure studied here, the crack remains confined in a single segment.

![Fig. 3.13 First crack in a segment](image)

In Fig. 3.14 the (mean) strain at crack onset of segments is shown for the various segment and gap size combinations, for the 1\textsuperscript{st} generation samples as well as for the 2\textsuperscript{nd} generation samples. The first number of each sample refers to the segment size, the second one to the gap size between the segments. It is seen that the mechanical reliability of the 2\textsuperscript{nd} generation samples is significantly improved. The improvement in mean tensile strain at onset of cracking improved
by 69% for the case with segments 450x450 μm and 120 μm gap size. For the case with segments 150x150 μm and 20 μm gap size, the improvement is even 260%.

![Graph showing mean strain for first crack for the 1st and 2nd generation samples]

Fig. 3.14 Mean strain for first crack for the 1st and 2nd generation samples

As said, during the tensile tests the resistance of the samples is also monitored. As mentioned before, all the resistive paths were connected in parallel at the two ends of the sample using a conductive adhesive paste. Before the actual loading, the initial resistance of the sample was measured. This initial resistance was slightly higher than expected on the basis of the theoretical resistances of the individual chains. This is seen to be due to the application of the conductive paste.

By recording the sample resistance during sample loading and thus registering the resistance changes, we obtain an indication on the degradation of the conductive chains (including the conductive past). Complete failure of all the conductive paths is indicated by recording an infinite resistance. The typical behaviour of a sample under increasing tensile load consists of a more or less continuous increase in sample resistance, with in some cases sudden changes (see Fig. 3.15). The sudden changes can be attributed to observed cracking of segments or metallic interconnects. Infinite resistance and various cracks (in segments or metallic interconnects) are found at a certain elongation.
Fig. 3.15 The resistance of the sample with square 150 segment size and 20 gap size under increasing tensile load.

Only in the case of the 150 by 150 µm square segment samples (20 µm gap) no cracks were observed at the segments until the complete loss of conductivity (at 1.86% strain). This indicates that failures of the metallic interconnects only are responsible for the loss in conductively.

Fig. 3.15 Strain for the degradation of conductive chains (=5% resistance growth) and total loss of conductance.

Fig. 3.15 presents the maximum (mean) strain reached for individual samples before total loss of conductivity (conductive chains failure) and the strain values for the first degradation (which is defined as 5% increase in resistance). The most sensitive case occurs for the sample
300 by 300 µm (gap 20 µm) where the first degradation occurs at a much lower strain value. The early failure might be due to processing defects in some of the conductive chains.

Fig. 3.16 Various failures of a stretched substrate

Fig. 3.16 shows a top view of a stretched substrate. Various damages can be seen, such as broken interconnects, shifted interconnects, segment cracks and various delaminations.

### 3.3.3 Bending tests

**Bending test setup**

The specially designed bending tool (as described in section 2.3.2., see Fig. 2.11.) was used to test the 2nd generation flexible and stretchable samples under bending around glass cylinders of various diameter. A connection foil was attached to the sample at the interconnection between aluminium foil and the sample (see Fig. 3.17). Again the sample was preloaded under tension via the connection tapes (ca. 0.1N). By lowering the two upper cylinders the sample was
wrapped around the glass cylinder. At the same time the resistance change was measured. Also images of the segments and interconnections were recorded with the optical microscope.

**Fig.3.17. Schematics of bending test setup with electrical connections via aluminium foils.**

**Bending test results**

In contrast to the previous observations for the 1st generation samples, now no damage of the segments was detected. Even the samples being bent around the cylindrical rod with 2 mm diameter did not show any damage. Also the resistance measurements did not show any resistance increase over the threshold value (= 5% resistance increase). So, it is concluded that the bending around the cylindrical rods for the 2nd generation samples is not critical.

**3.4 Simulations of flexible substrate behaviour**

**3.4.1 Introduction**

From the previously discussed experiments on the 2nd generation samples we observed various failures after complete over stretching (where the measured resistance became infinite), such as broken interconnects, shifted interconnects, segment cracks and various delaminations. However, the onset of failure (with resulting degradation of the electrical conductance) is likely to start in the wave shaped metallic interconnections and/or the poly-silicon supports structures. In order to gain more insight in the occurrence of these failures Finite Element simulations, with focus to the wave-shaped interconnections, were performed. Only the stretching of the samples
was simulated, because in the bending tests no failure was observed. The material parameters being used in the simulations are described in section 3.4.2.

In section 3.5 the FE models were adjusted to consider alternative shapes of interconnects. On the basis of these simulations a parameter optimization was finally performed to find the optimal interconnect shape.

### 3.4.2 Material properties

The material properties for polyimide, poly-silicon and silicon oxide were discussed in section 2.4.2 and were specified in Table 2. Compared to the 1st generation samples, we now have an additional material, being the aluminum used for the interconnections. The thin aluminium layer is considered as elastic-plastic material. We did not perform special experiments to establish the real elasto-plastic properties of the Aluminium interconnection lines. Instead we assumed properties by constructing an elastic plastic behaviour on the basis of measurement results as published by David (1994) for a Ti-Al-Ti line of thicknesses 0.1-2.0-0.1 μm. The Al-thickness is comparable with the thickness as used for our interconnection lines, although we do not have the thin layers of Ti on top and bottom. The actual stress-strain curve as given by [David 1994] is shown as the dashed line in the Fig.3.18. The Young’s modulus and Poisson’s ratio are 74GPa and 0.3, respectively. In [David 1994] it is also shown that the elasto-plastic behaviour is strongly dependent on the size of the metallic lines. Therefore, it is obvious that David’s stress strain curve can only be considered as a rough indication for the real material behaviour of our interconnection line. Therefore, we decided to not exactly copy the stress strain curve of David, but to simplify this by taken a linear hardening slope and steady plastic behaviour after reaching the ultimate strength 176 MPa (see Fig. 3.18.) The yield strength is taken as 124 MPa, The ultimate strength is reached at a strain of 1.0%. David’s stress-strain curve shows a softening behaviour after reaching the ultimate strength. Actually, no load is transferred at a strain of about 1.0%. With assuming a steady plastic deformation after reaching the ultimate strength, we do not include the softening path. This is considered allowable, as in our case the metallization is tightly connected to the poly-silicon support structure, which is believed to fail at a strain of about 1.4% (See next paragraph. See also the shaded part in Fig. 3.18.). Failure of the support structure will result in breakage of the metallization at the same time, being at 1.4% strain. The differences between our constructed stress-strain curve and the one of David is acceptable below a strain of 1.4%.
Taking a failure strain of about 1.4% for the poly-silicon support structure is supported by the work published in [Tsuchiya, 1998]. Here tensile tests were performed on thin poly-silicon lines of width comparable to the width of our support structure. In [Tsuchiya, 1998] the tester was constructed in a scanning electron microscope (SEM) chamber for in situ observation and was applied for tensile testing of polycrystalline silicon (poly-silicon) thin films with dimensions of 30–300 μm long, 2–5 μm wide, and 2 μm thick. The mean tensile strengths of non-doped and P-doped poly-Si were found as 2.0–2.8 and 2.0–2.7 GPa, respectively. Using the Young’s modulus of poly-silicon of 169 GPa, for the 5 μm wide poly-silicon interconnection support a failure strain between 1.18% and 1.59% is found. In the following we will consider the poly-silicon as broken at 1.4% strain.

It is quite difficult to link the increase in electrical resistance to the stress-strain behavior of the aluminum lines. Actually, no literature is found about the criterion, relating the resistance change to the plastic strain. Also, we did not perform separate investigations to this phenomenon. Nevertheless we will assume that no resistance change will occur as long as the Aluminum is still in the elastic state. It might be so, that in the plastic state the resistance is increased. On the other hand, during loading of the supported interconnection line, at some spots the aluminum will become plastic, although not directly over the whole cross section. Part of the cross section then can remain elastic while the remaining part is in the plastic range. This makes it extremely difficult to decide about the change in electric conductively. Mario Gonzalez (Mario Gonzalez e.a. 2008) designed copper interconnections for stretchable electronic circuits and investigated the metal interconnection failure by using max. stress as failure criterion. The “total work of plastic deformation” might be better correlated to the change in resistance.

![Stress-strain curve of aluminium film](image)

Fig.3.18. Stress-strain curve of aluminium film [David, 1994]
3.4.3 Finite element modeling

In section 2.4., for the 1st generation samples under stretching or bending, we described the use of Global-local FEM modelling as a good option to adequately deal with the large width (or length) to thickness ratio of the samples. This method could also well be used here for the 2nd generation samples. However, since we now restrict ourselves to square segments under stretching only, a simplified method can be used as well. Here we only use a local model, where the boundary conditions are obtained from the repeated symmetry in the sample. The local model used is made up from a single gap (of polyimide) with metallic interconnection + poly-silicon support structure, in between two embedded segments, such as illustrated in Fig. 3.19. (because of symmetry here only quarters of segments are used). The FE models were created using the Marc software using mechanical 3-D solid elements type 7. The model boundary conditions are specified in Fig. 3.19.

The boundary conditions include fixed x-direction displacement of nodes at the left hand boundary (AC), x-direction displacement loading of nodes at right hand boundary (BD), the y-direction displacements of the top nodes (AB) are the same, the y-direction displacements of the bottom nodes (CD) are the same, because of symmetry in the sample. Fig. 3.19 shows the cross section in the FE model, meshes and local meshes of different layers, especially the meshes of poly-silicon interconnection supports and aluminium interconnections.
Fig. 3.19 Schematics and mesh of FE model
3.4.4 Simulation results

Simulations are performed for elongation steps, increasing with 1% up to a maximum elongation of 10%. Fig. 3.20 shows the results for the first elongation step of 1%. The local maximum strains of the aluminium interconnection are found within the areas of the wave peak (at the inner side) and the connecting part between the wave interconnection and the segments. (At the latter location geometric singularities are present, with the possibility to give local stress singularities in the poly-silicon. These can not be captured by the present FE-model. For future interconnections such spots will be rounded off). A combination of tensile force and bending moment in the interconnection line (and support structure) are responsible for the maximum stress at the inside of the wave peak.

![Fig. 3.20. Max principle total strain distribution for the wave-shape interconnections under prescribed mean deformation (elongation) of 1%.]
The maximum stresses or maximum strains on the interconnections under the applied elongation steps, (increasing with 1% up to a maximum elongation of 10%), are thus established. Comparing the established maximum local stress with the failure stress (ultimate strength) makes it possible to find the sample elongation (or mean strain levels) at (assumed) onset of aluminium failure. These values are presented in Fig. 3.21.

It is shown here that the gap and segment size have influence on the mean strains at (assumed) onset of aluminium failure. The period number and amplitude and other factors also have effect on the maximum mean strain of interconnections. It should be noted that not only the segment sizes and gap sizes for square segments are used as variations, but also the interconnection data (See Table 3.1). Therefore it is concluded that the interconnecting shape design has apparently effect on the maximum mean sample strains. These results show that the optimization of the interconnect shape might be vital to improve the flexibility and stretchability of the samples. (This is discussed in section 3.5).

![Graph showing the mean strain at onset of interconnection failure](image)

**Fig. 3.21** The mean strain at onset of the interconnection failure (defined here as reaching the ultimate strength of the aluminum) as found from simulations

A comparison of the experimentally obtained strain values for a resistance change of 5% and the reach of the ultimate strength in the aluminium is shown in Fig. 3.22. In this figure, the first number indicates the segment size, the second one is gap size and the third one is wave cycle number. (The mean strain of a few samples is not available because of lack of samples). No good match between these strain values is found. Apparently the reaching of the ultimate
strength in the aluminium (at a local spot only) is not a good measure for the degradation of the electric conductivity.

Therefore (for future work), it is suggested to consider the “total work of plastic deformation” as a measure that could eventually be connected better to the change in conductivity.

![Graph showing mean strain at onset of interconnection failure](image)

**Fig. 3.22** The mean strain at onset of the interconnection failure (defined here as reaching the ultimate strength of the Aluminium) as found from simulations and obtained strain values for a resistance change of 5% found by experiments for the samples with square segments

### 3.5 Parameter sensitivity

FE simulation of wave shaped interconnections such as discussed previously can also be performed for alternative interconnection shapes. For example, just a straight interconnection and a semi-circular interconnection were also considered. The straight interconnections showed to have a much higher principal strain than all other cases (semi-circle and sinusoidal wave) under tensile loading. Also we did not succeed to create real samples with straight interconnections. Therefore this type of interconnection was not further considered. Just as we found for the sinusoidal interconnection, for the semi-circular interconnection again the maximum principal strain (or stress) in the aluminium is found at the inner side of the wave peaks as a result of combined normal stress and bending stress. But for comparable interconnection width and wave size, the sinusoidal case showed to be most favourable.
Therefore some parameter sensitivity simulations were performed for the sinusoidal interconnections only. These simulations were restricted to interconnections embedded into a gap of size 120 μm. (Although in the previous section the larger gap size of 200 μm appeared to be more favourable, this size was chosen to facilitate easy comparison with the 1st generation samples.) Parameters being varied are: 1. The width of the interconnection (range: 2-5 μm). 2. The number of half waves (range: 2-6). 3. The amplitude of waves (range: 20-100 μm).

Comparing the established maximum local stress with the ultimate strength makes it possible to find the “sample mean strain” at (assumed) onset of aluminium failure. This “sample mean strain” as established for certain parameter combinations are presented in Figs. 3.23 and 3.24.

![Sample Mean Strain vs Interconnection Width](image)

Fig. 3.23 The “sample mean strain” at (assumed) onset of failure of a sample with amplitude 40 μm and number of half waves=2 versus the interconnection width.
Fig. 3.24 The “sample mean strain” at (assumed) onset of failure of a sample with interconnection width=2 μm versus the wave amplitude for various half wave numbers.

From Fig. 3.23 we learn that the sample mean strain increases with decreasing interconnection width (for a sample with amplitude 40 μm and number of half waves=2). From the Fig. 3.24 it is seen that the sample mean strain increases with increasing wave amplitude (for a sample with interconnection width=2 μm). A minor influence of the number of half waves is observed.

The “sample mean strain” apparently can not reach more than 7% for all cases being considered. In case that the interconnection would not be embedded in polyimide, it would nicely behave as a flexible spring and a much larger “sample mean strain” could be expected (See also Chapter 4). Apparently the embedding of this spring in polyimide reduces the “sample mean strain” at onset of failure very much. This is the reason that in Chapter 4 first of all embedding in a much softer material is tried out. Also the case of a completely free interconnection (not embedded) is considered there.

So far, for the above embedded samples some parameter sensitivities were established. A complete parameter optimization was not performed because the observed limited flexibility for all considered interconnection shapes and parameter sets.
3.6 Conclusion

The 2nd generation samples were designed and fabricated with fully segmented polycrystalline silicon segments and a flexible aluminium interconnection supported by polysilicon between the poly-silicon segments. The samples being considered have varying segment sizes (from 150 to 450 μm) and varying segment spacings (from 20 to 200 μm). Various (more or less) sinusoidal interconnections were chosen with several numbers of half waves and various wave amplitudes.

When the samples were bent around the (smallest) cylindrical rod with 2 mm diameter, no damage of the segments was detected. The resistance measurements did not show any resistance increase over the threshold value.

Compared to the 1st generation samples, for tensile testing of the 2nd generation samples the (mean) strain at onset of failure (=segment cracking) is significantly improved, but appears yet to be limited till about 1.86% (for the case with segments 150x150 μm and 20 μm gap size). That is an improvement with 260% compared to the onset of failure of the comparable 1st generation sample.

In order to gain more insight into the occurrence of interconnection failures various local FE simulations were performed for wave-shaped interconnections of samples with square segments (under stretching only). The local model used is made up from a single gap (of polyimide) with metallic interconnection and poly-silicon support structure in between two embedded segments. Comparing the experimentally obtained strain values for a resistance change of 5% and the “sample mean strain” at (assumed) onset of failure, did not give a good match. Probably the assumed onset of failure, defined by reaching the ultimate strength in the aluminium (at some local spot only) is not a good measure for the degradation of the electric conductivity. The “total work of plastic deformation” might be better correlated to the change in resistance.

The sinusoidal wave interconnection shows the best performance compared to the straight interconnection and the semi-circular interconnection. The influence of wave amplitude, number of half waves and line width of the sinusoidal interconnection is explored. However, the sample mean strain at onset of interconnection failure appears to be limited to a few percents only (7% for the best case). Here it is realized that from the experiments the occurrence of segment cracking was found even at lower sample mean strain values (1.86% for the case described above). From both the experiments and the interconnection FE simulations it is concluded that again insufficient flexibility and stretchability is obtained for all considered
interconnection shapes. It is believed that this is caused by the embedding of the segments and interconnections within the polyimide. For this reason in the next chapter embedding in a much softer material is worked out. Also the case of a completely free interconnection (not embedded) is considered there. In this manner a new concept of future flexible and stretchable substrates will be introduced.

References


Chapter 4

Future Flexible and Stretchable Substrate I

4.1 Introduction

The concept of a so-called 1\textsuperscript{st} generation flexible and stretchable substrate was discussed in Chapter 2. Here thin silicon segments were embedded into a polyimide layer. It was found that the mechanical behavior appeared to be disappointing as the experimental and FE simulation results showed the occurrence of cracks at early stage of deformation. To improve the mechanical reliability we designed the 2\textsuperscript{nd} generation samples where not only the silicon layer but also all dielectric layers were segmented. Also electrical connections between the silicon segments were realized by introducing aluminium layers on poly-silicon support structures bridging the gaps. The mechanical behaviour and the degradation of the electrical paths of the 2\textsuperscript{nd} generation samples were extensively explored. But from both the experiments and the FE simulations it was concluded that again insufficient flexibility was obtained for the considered interconnection shapes. It was assumed that this was caused by the embedding of the segments and interconnections within the polyimide, which is supposed to be not flexible enough. Therefore, in the present chapter embedding in a much softer material (silicone rubber) is worked out. The concept is similar to that in Chapter 3 except silicone rubber replacing polyimide as embedding material. Next in Chapter 5 the case of a completely free interconnection (not embedded) is also considered. In this manner new concepts of future flexible and stretchable substrates are introduced.
The actual fabrication of the next generation samples and the testing will be performed within a continuation of the present project by other Ph.D. students. In order to be able to forecast the mechanical behaviour of the next generation flexible samples by simulation, adequate mechanical properties of the silicone rubber being used are required. Therefore various mechanical tests are carried out on silicone rubber foil. Among these are cyclic deformation tests, tensile tests (until rupture) and double shear tests. It is also important to check whether the material behaviour is time dependent or not (at room temperature). Here it is interesting to know the glass transition temperature (and how much this deviates from room temperature). Therefore analysis of visco-elastic properties by (small strain) Dynamic Mechanical Analysis (DMA) is also performed.

In order to explore the possible improvement in mechanical behaviour of the substrates by using silicone rubber instead of polyimide as encapsulating material, the FE simulations as reported in Chapter 3 were repeated here, but now using the established rubbery constitutive model. The simulation results are presented in Section 4.3 and are compared with the previous results from Chapter 3.

4.2 Constitutive model for silicone rubber

In order to be able to explore the mechanical properties of flexible and stretchable substrates, where the embedding material is silicone rubber, an adequate constitutive model is necessary. This section considers the mechanical characterizations being performed to obtain this constitutive model. Silicone rubber is a relative soft material with visco-elastic and large deformation properties. It is expected that at room temperature the material is in its rubbery state. Visco-elastic behavior is expected at temperatures (far) below room temperature.

The characterization of silicone rubber includes large deformation tensile testing at room temperature to establish the model parameters of a suitable rubber elasticity model. From cyclic tensile testing it is found that apart from the Mullin’s effect at the 1st cycle the material behaves hyper elastic. Visco-elastic effects appear to be negligible at room temperature. In order to explore at what temperatures visco-elastic effects could become important we also performed a (small strain) Dynamic Mechanical Analysis (DMA) over a temperature range from -100 °C till +100 °C.
4.2.1 Tensile testing

Tensile tests on fully cured silicone rubber foil were performed to investigate the rubber non-linear deformation behaviour at room temperature. The silicone rubber was cured at 100°C for one hour and post cured at 150°C for one hour. The samples were prepared between two glass plates with controlled gap size. After preparation, the sample dimensions were 7.33 mm in length, 4.22 mm in width and 30 μm in thickness. The foil samples were clamped at the ends and then subjected to tensile deformation in a TA Q-800 tester. First a (strain controlled) cyclic tensile testing was performed. Some of the results (engineering stress and engineering strain) are presented in Fig. 4.1

![Fig. 4.1. Cyclic loading and unloading tensile test results for silicone rubber at room temperature (number of cycles=10)](image-url)

It is found that after a few cycles the engineering stress-strain behaviour stabilizes. The behaviour in the first few cycles can be attributed to the Mullin’s effect [Ernst, et.al, 1999] and possibly some slipping at the clamps. As we find that the stress-strain behaviour stabilizes after a few cycles, it can be concluded that at room temperature visco-elastic effect are negligible.
From a single tensile test, loaded until failure (see Fig. 4.2) a failure strain of about 176% was found. Since the failure initiation was at the clamps (where strain localisation will be present) the real failure strain for the silicone rubber could even be higher. For comparison, for the polyimide used in Chapter 3 the ultimate tensile strain is specified as less than 10% (from the provider’s data sheet). From Fig. 4.2 the (initial) Young’s modulus of silicone rubber at room temperature is found ($E_{\text{rubber}} \sim 1.7$ MPa). The same value was found from (small strain) DMA analysis (see section 4.2.2). For comparison, the Young’s modulus of the polyimide as used in Chapter 3 is 3.3 GPa (from the provider’s data sheet). It can be concluded that because of the softness of silicone rubber it should be more adequate as embedding material for future generation samples.

### 4.2.2 Exploration of visco-elastic behavior

We have seen that visco-elastic effects appear to be negligible at room temperature. In order to explore at what temperatures visco-elastic effects could become important we also performed a (small strain) Dynamic Mechanical Analysis (DMA) over a temperature range from -120 °C till +100 °C. Here the temperature scanning tests were performed on the TA-Q800 DMA equipment using scanning frequencies 0.5, 1, 3.2, 10,32 Hz.

The viscoelastic material not only shows time dependent behaviour but also strong temperature dependent behaviour. At low temperature visco-elastic materials behave glassy and exhibit a plateau of a relatively high (shear) modulus, called the glassy plateau. In this region,
the material is hard and brittle. As the temperature is increased, the material goes through the transition region and the (shear) modulus drops dramatically and becomes time and/or frequency dependent. The glass transition occurs over a certain temperature range around the so-called glass transition temperature \( T_g \). As the temperature is increased further, the modulus reaches another plateau, where the time or frequency dependence vanishes, the so-called rubbery plateau. Generally, here the material also becomes incompressible. The glassy plateau (shear) modulus of the silicone rubber (as established by DMA analysis) is \(~380\) MPa for temperatures below \(~-105°C\). The rubbery plateau (Young’s) modulus of the silicone rubber is \(~1.70\) MPa at the temperature above \(~-15°C\). The glass transition temperature \( T_g \) is found at \(-45.35°C\) (\( T_g \) is here defined as the temperature where the max viscous damping is established, for DMA testing at \(1\) Hz).

### 4.2.3 Modeling of rubber elastic behavior

At room temperatures, the stress-extension response of typical rubbers is characterized by the hyper-elastic behaviour. In the past, many rubber hyper-elastic models which try to describe this kind of long range elastic behaviour have been proposed. In the rubber hyper-elastic descriptions two major classifications often arise. A first group tries to describe the rubber hyper-elasticity based purely on experimental observations, the so-called *phenomenologically-based models*. This type of theories have been described in many literatures, see for instance Mooney (1942), Rivlin (1948), Ogden (1984), Treloar (1958, 1975) and more recently Van den Bogert (1991).

A second group tries to describe the rubber hyper-elasticity by employing the macroscopical nature of the rubber molecular structure, i.e. so-called *molecular-based models*. One common characteristic of the models from this group is the capability of describing a wide-range of rubber deformation behaviour independent of the number of model parameters. Also the implementation of time-dependent behaviour through alteration of the molecular structure appeared quite well possible based on this theory [Septanika, et al, 1998].

For the present FE simulations, necessary to forecast the mechanical behaviour of the next generation flexible samples, the Mooney-Rivlin type of models are used, mainly because these are already present in the MARC FE program. We just have to provide the necessary model parameters by fitting experimentally obtained stress-strain data from the tensile experiment. The adequacy of the obtained model is tested by verifying the model results and experiment results
of a double shear test. As a result we conclude that for the present goal the Mooney-Rivlin models are sufficiently accurate.

**Review of Mooney models**

As discussed before the silicone rubber behaviour will be modelled using Mooney models for application in our FE simulation results. Here first a review of available Mooney models is presented.

Calculation of stresses according to elasticity models require a strain energy function. The strain energy function \( W \) is usually defined in terms of strains or alternatively strain invariants or principal stretches.

The earliest Mooney models [Mooney, *et al.*, 1940, Morman, *et al.*, 1986] use the invariants \( I_i \) of the Right Cauchy-Green stretch tensor \( C \) to express the strain-energy function

\[
W = W(I_1, I_2, I_3)
\]

[4.1]

An alternative description (used in the MARC FE code theoretical manual) uses the principle stretches \( \lambda_i \) of the Right Cauchy-Green stretch tensor \( C \).

\[
W = W(\lambda_1, \lambda_2, \lambda_3)
\]

[4.2]

The strain invariants and these principle stretches are related as follows:

\[
\begin{align*}
I_1 &= \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \\
I_2 &= \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2 \\
I_3 &= \lambda_1^2 \lambda_2^2 \lambda_3^2
\end{align*}
\]

[4.3]

Generally, the strain energy function is split into deviatoric and volumetric parts as follows:

\[
W = W_{\text{deviatoric}} + W_{\text{volumetric}}
\]

[4.4]

The Mooney models assume full incompressibility \( (I_3=1, \text{ which in the MARC FE code is enforced by using Lagrangian multipliers}) \) and thus the description is focussed to the deviatoric part only.
The general formulation is given by:

\[ W_{\text{deviatoric}}^{\text{gmr}} = \sum_{m=1}^{N} \sum_{n=1}^{N} C_{mn} (\overline{T}_1 - 3)^m (\overline{T}_2 - 3)^n \]  

[4.5]

Here the bar on \( I_1 \) and \( I_2 \) refers to the invariants of the deviatoric parts of the Right Cauchy-Green stretch tensor \( \mathbf{C} \). The superscript “gmr” refers to “Generalized Mooney-Rivlin” Model.

A particular form of this generalized Mooney-Rivlin model is the so-called third order: deformation model that is written as follows:

\[ W_{\text{deviatoric}}^{\text{tod}} = c_{10} (\overline{T}_1 - 3) + c_{01} (\overline{T}_2 - 3) + c_{11} (\overline{T}_1 - 3)(\overline{T}_2 - 3) + c_{20} (\overline{T}_1 - 3)^2 + c_{30} (\overline{T}_2 - 3)^2 \]  

[4.6]

(The superscript “tod” refers to “Third Order Deformation” model):

Where \( W_{\text{deviatoric}}^{\text{tod}} \) is the deviatoric third order strain energy function and \( c_{10}, c_{01}, c_{11}, c_{20}, c_{30} \) are material constants obtained from experimental data. Simpler and popular forms of the \([4.6]\) strain energy function are obtained as:

\[ W_{\text{deviatoric}}^{\text{Mooney–Rivlin}} = c_{10} (\overline{T}_1 - 3) + c_{01} (\overline{T}_2 - 3) \]  

[4.7]

The components of the 2\(^{nd}\) Piola Kirchhoff stress tensor (with respect to the base vectors in the undeformed state) are defined as:

\[ S_{ij} = \frac{\partial W}{\partial E_{ij}} \equiv 2 \frac{\partial W}{\partial C_{ij}} \]  

[4.8]

Here \( E_{ij} \) represent the components of the Green-Lagrange strain tensor (with respect to the base vectors in the undeformed state). These are related to the components of the right Cauchy-Green deformation tensor by:

\[ E_{ij} = \frac{1}{2} (C_{ij} - \delta_{ij}) \]  

[4.9]

In order to establish the coefficients in the expressions \([4.6]\) and \([4.7]\) the tensile test data are fitted to the stress-strain expression according to \([4.8]\).

For a simple tensile test on a long cylindrical sample with the 1-axis in longitudinal direction, one principle stretch is found in the 1-direction as illustrated in Fig. 4.3.
This principle stretch in longitudinal direction is related to the Lagrangian strain in this direction, $E_{11}$ by:

$$E_{11} = \lambda_1 - 1 \quad \text{[4.10]}$$

According to [4.6] the 2nd Piola Kirchhoff stress component in the 1-direction (=longitudinal) is given by:

$$S_{11} = \frac{\partial W}{\partial E_{11}} \quad \text{[4.11]}$$

Various formulations for Mooney are available in Marc. After fitting the tensile test data (see Fig. 4.2) the coefficients of the Mooney model can be obtained, the Mooney constants and the least square error for the silicone rubber are listed in Table 4.1. The fitted stress-strain curves are presented in Fig. 4.3. As seen the 3rd order deformation model fits best to the stress-strain data. Therefore it is decided to use this model for the simulations of the flexible substrates later. Before doing so, verification of the various models under shear conditions are first performed. These verifications are presented hereafter.

**Table 4.1 The Mooney model coefficients for silicone rubber**

<table>
<thead>
<tr>
<th>Model</th>
<th>$C_{10}$</th>
<th>$C_{01}$</th>
<th>$C_{11}$</th>
<th>$C_{20}$</th>
<th>$C_{30}$</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOONEY(3)</td>
<td>1.70739</td>
<td>-2.01245</td>
<td>-0.09404</td>
<td></td>
<td></td>
<td>0.06694</td>
</tr>
<tr>
<td>SIGNORINI</td>
<td>1.50387</td>
<td>-1.78468</td>
<td>-0.02989</td>
<td></td>
<td></td>
<td>0.05975</td>
</tr>
<tr>
<td>2nd ORDER INVARIANT</td>
<td>-2.87864</td>
<td>3.6407</td>
<td>1.4506</td>
<td>-0.43176</td>
<td></td>
<td>0.0099</td>
</tr>
<tr>
<td>3rd ORDER DEFORMATION</td>
<td>-0.85428</td>
<td>1.30274</td>
<td>0.15233</td>
<td>0.12401</td>
<td>-0.01377</td>
<td>0.00746</td>
</tr>
</tbody>
</table>

Fig. 4.3 Rectangular block rubber
Fig 4.3 The Mooney model fitting and the tensile test curves

**Model Verification with shear test**

Double shear tests were done to verify the chosen 3rd order Mooney-Rivlin model for its applicability to shear deformation problems. The shear tests were executed on a DMA TA-Q800 tester at room temperature, the sample dimensions are 10 x 10 x 3.51 mm in length, width and thickness, respectively. The shear force and shear angle can be obtained.

Fig. 4.4 The shear stress against shear angle for test and simulations
In Fig. 4.4, the simulation results with the various Mooney models are presented together with the measurement data. It can be concluded that the chosen 3rd order deformation model again fits best to the experimental data and the silicone rubber can be accurately characterized by this Mooney model.

4.3 FE simulation

FE simulations were performed to investigate the influence of silicone rubber on the flexibility and stretchability of the samples. The same FE model used is similar to that used for the 2nd generation samples in Chapter 3. However, now the polyimide layer is replaced by 30 μm silicone rubber layer. The embedding material silicone rubber is treated with the 3rd order deformation Mooney model (shown in the previous section).

The square sample with size 450 μm, 200 μm gap size and 2 half wave interconnections is considered to compare with that in Chapter 3. The investigation focuses on the possible onset of cracking of segments and on possible failure of the interconnection.

Simulations are performed for elongation steps, increasing with 1% up to a maximum elongation of 200%. Fig. 4.5 shows the maximum principle strain distribution on the Si segments and support structure for the first elongation step of 1% for the test structure embedded into silicone rubber.

Fig. 4.6 shows the maximum principle strain distribution on the silicon segments for the first elongation step of 1% for the test structure embedded into polyimide. The strain concentrations in the silicon segment are found within the transition of the (silicon) interconnection support and the silicon segment. However, the (max) principle strain concentration in the case with silicone rubber is much less than in the case with polyimide.
Fig. 4.5 Max principle strain distribution for the Si segment and the Si support structure embedded into silicone rubber under prescribed mean deformation (elongation) of 1%.

Fig. 4.6 Max principle strain distribution for the silicon segment and silicon support structure embedded into polyimide under prescribed mean deformation (elongation) of 1%.
For the case of embedding the segments into polyimide, the sample mean strain at crack initiation (note that than the mean strain \(\gg 1\%\)) in the Si interconnection support and the Si segment (according to the failure criterion for the Si, see [3.4.2]) was found to be about 2.86\% and 2.2\%, respectively. In the case of embedding into silicone rubber, these values appear to be increased to 4.99\% and 259\%. So the replacement of polyimide by silicone rubber very much improves the fracture behaviour of the Si-segments. However, the improvement for the support structure is about a factor 2 only.

For the silicone rubber we have established a failure strain of 176\% (see the tensile results in the previous section). In case of the maximum mean strain of 135\%, the maximum principle strain in the silicone rubber was found to be at the failure level of 176\%. Based on the above limit strain values, it is expected that when increasing the mean sample strain, first the Si support structure will fail, subsequently the silicone rubber will fail. Failure of the Si-segments is thus likely not to occur at all.

What we did not consider so far is the possibility of delamination failure between silicone rubber and silicon.

4.4 Conclusion

A new concept of a flexible and stretchable substrate was discussed. Here the segments and interconnections are fully embedded into silicone rubber. Proper material properties of silicone rubber are essential for getting insight into the mechanical behavior of the new design through FE modeling. In particular, FE modeling is used to forecast possible failure. The mechanical properties of silicone rubber were characterized by various methods including tensile testing, cyclic tensile testing and DMA. The ultimate tensile elongation of the silicone rubber foil can reach about 176\% at room temperature. The visco-elastic behaviour of the silicone rubber is not apparent at room temperature. The 3\(^{rd}\) order Mooney model was selected for the constitutive description of the silicone rubber and its application to the FE simulations of the next generation sample as proposed in this Chapter (the future flexible and stretchable substrate I).

Based on the FE simulation results, it is expected that when increasing the mean sample strain, first the Si support structure will fail and subsequently the rubber will fail. Failure of the Si-segments is likely not to occur at all. However, we did not explore possible delamination failure between silicone rubber and silicon.
Compared to the 2\textsuperscript{nd} generation sample (as discussed in Chapter 3), the present concept only gives an improvement of about a factor 2 for the mean strain level at 1\textsuperscript{st} failure occurrence. The limiting factor for the improvement is the disappointing behavior of the Si-support structure. Apparently, the embedment of the Si-support structure by silicone rubber very much reduces the spring behavior of the sinusoidal support structure. Therefore, in the next Chapter a major improvement is suggested, by not completely embedding the support structure by silicone rubber, but only sandwiching this structure between two silicone rubber foils.

\textbf{References}


Chapter 5

Future Flexible and Stretchable Substrate II

5.1 Introduction

The 1st and 2nd generation flexible and stretchable substrates were discussed in Chapter 2 and 3 with the test structure embedded into polyimide. The mechanical behavior appeared to be disappointing as the experimental and FE simulation results showed the occurrence of cracks on segments and failures on the interconnections at early stage of deformation. Next, in Chapter 4, a future flexible and stretchable substrate concept was introduced. Here the segments and interconnections were embedded into silicone rubber. As discussed in Chapter 4, in this concept the Si-segments probably will not appear to crack. However, it was shown that this concept only gives a limited improvement for the interconnections on the Si-support structure. Apparently, the embedment of the Si-support structure by a (soft) material very much reduces the spring behavior of the sinusoidal support structure.

In the present chapter a major improvement is first suggested, by not embedding the interconnections on Si-support structures by any (soft) material, but only sandwiching the structures between two silicone rubber foils. In this concept, the silicon segments are bonded to the silicone rubber foils (fully or partly), but interconnections between segments would not contact the silicone rubber foils. In this case it is expected that the spring behavior of the structures is fully made available. However, with this improvement the limiting factor on the
elongation of the springs is the fact that the Si-support structure is quite brittle. That means that after reaching the ultimate tensile stress abrupt failure will occur, subsequently followed by rupture of the supported metallization. In a second improvement it is suggested to remove the Si-support structure completely, such that a free-standing metallic spring remains. The free-standing metallic spring will to a certain extent behave ductile. This is expected to give a further improvement of the interconnection concept. To further improve the ductility of the metallic spring, as a third improvement it is suggested to change over from aluminum to copper.

Of course, the suggested changes have severe implications to the manufacturing process. These implications are to be considered in a next Ph.D. project.

In the present chapter the flexibility and reliability of the free-standing copper interconnections is explored. Because of the better electrical and mechanical performance copper interconnections are chosen to replace aluminum [J. Torres, 1995]. Several geometries of spring structures are numerically tested. As a result a final interconnection shape is advised for further evaluation, fabrication and testing.

5.2 Free-standing interconnection design

As said, several shapes of copper interconnections are evaluated. In particular meander, horseshoe and mesh shaped interconnections are considered. Each type of structure is created by repeating a base element having a chosen set of parameters: The width of the copper line, the spacing between the copper lines, a certain length, some angles and/or radii of curvature.

The meander structure is made of parallel beams with width $W$ and length $L$ being connected by curved beams made up from circular parts with radii of curvature $R$ (of the centre line), the same width $W$ and an angle $\alpha$, thus having $(W, L, R, \alpha)$ as the defining parameters (see Fig. 5.1),

The horseshoe design is derived from the meander structure, but now the straight beam parts are omitted, the geometric parameters $(W, R, \alpha)$ are defined in (See Fig. 5.2).

Meshed shape interconnections are created by replicating a rectangular ring element as a base. The geometric parameters $(W, L, D, d)$ are defined in Fig 5.3.
Fig. 5.1. Illustration of the meander interconnection with various parameters

Fig. 5.2. Illustration of the horseshoe interconnection with various parameters

Fig. 5.3. Illustration of the mesh interconnection with various parameters: mesh base element (left) and 4x2 mesh (right).
The parameters used are specified in Tables 5.1, 5.2, 5.3. The parameter combinations being considered are: 26 for the meander design, 35 for the horseshoe design and 27 for the 4x2 mesh design (some parameter combinations were omitted as these generated unusable structures).

Table 5.1. Meander Interconnect parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values (µm or °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle α</td>
<td>0, 15, 30</td>
</tr>
<tr>
<td>Width W</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>Radius R</td>
<td>10, 50, 100</td>
</tr>
<tr>
<td>Length L</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 5.2. Horseshoe Interconnect parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values (µm or °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle α</td>
<td>0, 15, 30, 45</td>
</tr>
<tr>
<td>Width W</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>Radius R</td>
<td>10, 50, 100</td>
</tr>
</tbody>
</table>

Table 5.3. Mesh interconnect parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values (µm or °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width W</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>Distances D, d</td>
<td>5, 10, 20</td>
</tr>
<tr>
<td>Length L</td>
<td>100, 300, 500</td>
</tr>
</tbody>
</table>

5.3 FE simulation of free-stand interconnection

When exploring the suitability of the new designs to survive large extensions, the limiting factor for failure is assumed to be the ultimate equivalent strain in the copper. FE simulations for the various designs are performed using the Marc FE program. The material properties used for the FE analyses are first discussed.

Material properties

The thin copper layer is considered as an elastic-plastic material. Experiments are not performed to establish the real elasto-plastic properties of the Copper interconnection lines.
Instead an elastic plastic behaviour is assumed in the present simulations on the basis of measurement results as published by M. Dao (2006) for a Cu line of a thicknesses only a few microns. This Cu-thickness is comparable with the thickness as used for our interconnection lines. The actual stress-strain curve as given by Dao is shown as the dashed line in the Fig. 5.4. The Young’s modulus and Poisson’s ratio (in the elastic region) are 128 GPa and 0.36, respectively. In [M. Dao 2006] it is shown that the elasto-plastic behaviour is strongly dependent on the grain size. Therefore, it is obvious that Dao’s stress strain curve can only be considered as a rough indication for the real material behaviour of our interconnection line (The process of making the Cu lines is still to be decided). Therefore, we decided to not exactly copy the stress strain curve, but to simplify this by using a linear hardening slope and steady plastic behaviour after reaching the ultimate strength (see Fig. 5.4.). The ultimate strain according to Dao’s measurements is 11.6%. In the FE simulation results, reaching this ultimate strain value will be used as a failure criterion, although when this just occurs locally the whole structure is not really failed and electrical conduction will hardly be affected.

![Stress-strain curve of copper film](image)

**Fig. 5.4.** Stress-strain curve of copper film, dashed line is measurement results according to [M. Dao, 2006], solid line is constructed bi-linear behaviour as used in the FE simulations

**Finite element modeling**

As said all interconnections are made up from repetition of basic shapes (see Figs. 5.1, 5.2 and 5.3). As a result, based on symmetry considerations FE simulations can be restricted to the basic shapes only. The models used are illustrated in Figs. 5.5a-c. 3-D solid elements (MARC) type 7 are used. The boundary conditions include fixed x-direction displacement of nodes at the left end and prescribed x-direction displacements on all boundary nodes at the right end. The rigid body movements are additionally suppressed.
Fig. 5.5 FE models of free-standing interconnection base parts
   a. meander, b. horseshoe c. mesh

**FE simulation results for the meander structure**

For these meander base parts, simulations are performed for elongation steps, increasing with 5% up to a maximum elongation of 1500%. The maximum equivalent strain on the interconnections under the applied elongation steps are thus established. Comparing the established maximum equivalent strain with the failure strain (ultimate strain) makes it possible to find the sample elongation (or mean strain level) at (assumed) onset of failure.

Fig. 5.6. Equivalent strain distribution for the meander interconnections under prescribed mean deformation (elongation) of 20%. (W=20 μm, R=100 μm and α=15 degree)
Figure 5.6 shows the equivalent strain distribution at an elongation of 20% for a meander interconnection (W=20 μm, R=100 μm and α=15 degree). The maximum equivalent strains of the free-standing meander interconnections are found within the area of the wave peak (at the inner side). A combination of tensile force and bending moment in the interconnection line is responsible.

For comparison, note that corresponding mean elongation results for the embedded wave shaped interconnections for elongations of 1% are given in Figs. 3.20 (embedded in polyimide) and 4.5. (embedded in silicone rubber). It can be concluded that the free-standing (meander-) interconnection behaves much better than the previously discussed embedded interconnections.

Fig. 5.7. The mean strain at onset of failure (defined here as reaching the ultimate strain of the copper) of the meander shape interconnection, for various model parameter sets (width W, radius R and angle α).

For the meander shape interconnections, the mean strain at onset of failure (defined here as reaching the ultimate strain of the copper) is presented in Fig 5.7. for various model parameter sets (width W, radius R and angle α). It is found that the behaviour improves with larger radius R and smaller width W. Also the increase of the angle α has a positive influence. From the parameter sets being considered the best result (being the one with the highest mean strain) is found for W=5 μm, R=100 μm and α=30 degree. For this case the equivalent strain distribution at maximum elongation (1375%) is presented in Fig. 5.8.
Fig. 5.8. Equivalent strain distribution for the meander interconnections under prescribed mean deformation (elongation) of 1375%. (W=5 μm, R=100 μm and α=30 degree)

Compared to the results in the previous chapters it can be concluded that an enormous improvement of the stretchability of the interconnect structure is found. It should be noted, that on the basis of the set failure criterion for the most favourable case a mean strain of about 1375% is found. Here it should be realized that in this case the maximum mean strain of the substrate (with silicone rubber sheets covering the Cu-interconnect) will be limited by the maximum mean strain that other parts can withstand. For example, the maximum mean strain of the silicone rubber sheets is expected to be limited to about 176%, or less according to the measurement results given in Section 4.2.1.

Therefore the behaviour of the Cu interconnect up to 176% mean strain is also quite interesting. For the best case in Fig. 5.7. (the parameter values W=5 μm, R=100 μm and α=30 degree), the established equivalent strain for this mean elongation is presented in Fig. 5.9

Fig. 5.9. Equivalent strain distribution for the meander interconnections under prescribed mean deformation (elongation) of 176%. (W=5 μm, R=100 μm and α=30 degree)
For the meander interconnection with the most favourable model parameter sets (W=5 μm, R=100 μm and α=30 degree) under the prescribed mean elongation of the silicone rubber ultimate strain of 176%, the maximum local equivalent strain at the inner wave peak is only 0.64%. This is lower than the elastic strain of Copper, which is 0.67%. As a result, the meander interconnection (W=5 μm, R=100 μm and α=30 degree) will behave fully elastic and thus will not be damaged, even not under cyclic elongation.

**FE simulation results for the horse shoe structure**

Simulations are performed for elongation steps, increasing with 5% up to a maximum elongation of 300% for the horseshoe base parts. The maximum local equivalent strains on the interconnections are obtained under the applied elongation. The sample elongation (or mean strain level) at (assumed) onset of failure is found by comparing the established maximum equivalent strain with the failure strain (ultimate strain).

![Horseshoe interconnection simulation](image)

**Fig. 5.10.** Equivalent strain distribution for the horseshoe interconnection (with W=10 μm, R=50 μm and α=45 degree) under prescribed mean deformation (elongation) of 20%.

Fig. 5.10 shows the equivalent strain distribution at an elongation of 20% for a horseshoe interconnection with W=10 μm, R=50 μm and α=45 degree. The maximum equivalent strain of the free-standing horseshoe interconnection is found within the area of the wave peak (at the inner side). A combination of tensile force and bending moment in the interconnection line is responsible.
Fig. 5.11. The mean strain at onset of failure (defined here as reaching the ultimate strain of the copper) of the horseshoe shaped interconnection, for various model parameter sets (width W, radius R and angle $\alpha$).

For the horseshoe shape interconnections, the mean strain at onset of failure is presented in Fig. 5.11 for various model parameter sets (width W, radius R and angle $\alpha$). It is found that the behaviour improves with larger radius R and smaller width W. Also the increase of the angle $\alpha$ has a positive influence. The maximum mean strain of the sample can reach 250% for the parameter set W=5 $\mu$m, R=100 $\mu$m and $\alpha$=45 degree.

**FE simulation results for the mesh structure**

Simulations are performed for elongation steps, increasing with 5% up to a maximum elongation of 500% for the mesh based parts. The maximum local equivalent strains on the interconnections are obtained under the applied elongation. Sample elongation (or mean strain level) at (assumed) onset of failure can be found by comparing the established maximum equivalent strain with the failure strain (ultimate strain).
Fig. 5.12. Equivalent strain distribution for the mesh interconnection with (W=20 μm, D=20 μm and L=500 μm) under prescribed mean deformation (elongation) of 20%.

Fig. 5.12 shows the strain distribution at an elongation of 20% for the mesh interconnection with W=20 μm, D=20 μm and L=500 μm. The local maximum equivalent strain of the free-standing mesh interconnection is found at the inner side of the vertices. A combination of tensile force and bending moment is responsible for this maximum equivalent strain.

Fig. 5.13. The mean strain at onset of failure (defined here as reaching the ultimate strain of the copper) of the mesh shape interconnection, for various model parameter sets (beam length L, width W and distance D).

For the mesh shaped interconnections, the mean strain at onset of failure is presented in Fig. 5.13. for various model parameter sets (width W, length L and distance D). It is found that the behaviour improves with larger length L and smaller width W. Also the increase of the distance
D has a positive influence. The maximum mean strain of the sample can reach 450% for the meshed interconnection with beam length L 500μm, width W 5 μm and distance D 5 μm.

5.4 Conclusion

The future flexible and stretchable substrate concept II was discussed. Here free-standing interconnection copper lines, sandwiched in between silicone rubber sheets, connect the Si-segments. Three types of the interconnections, meander shaped, horseshoe shaped and meshed shaped, were designed with various parameter sets. Simulations for the basic parts were performed to evaluate the influence of the geometric parameters on the flexibility and stretchability. The free-standing interconnection shapes and their geometric parameters have significant influence on the stretchability.

From the three types of interconnections being considered, the meander shaped design appears to be most favourable. Compared to the results in the previous chapters it can be concluded that an enormous improvement of the stretchability of the interconnect structure is found. It is realized that because of the enormous flexibility of the meander shaped interconnection design, the maximum mean strain of the substrate (with silicone rubber sheets covering the Cu-interconnect) is limited by the maximum mean strain that other parts can withstand. The maximum mean strain of the silicone rubber sheets is limited to about 176%, or less. Therefore the behaviour of the Cu interconnection up till about 176% mean strain is considered as quite interesting. For the most favourable case (W=5 μm, R=100 μm and α=30 degree), the established equivalent strain for this mean elongation is found to be 6.439e-3 only. This is below the elastic strain limit of the Copper. As a result, the meander interconnection (W=5 μm, R=100 μm and α=30 degree) will behave fully elastic and thus will not be damaged, even not under cyclic elongation.
References


Nano-sized twins induce high rate sensitivity of flow stress in pure copper

Strength, strain-rate sensitivity and ductility of copper with nano-scale twins
6.1 Review

A promising flexible and stretchable substrate concept based on vertical thinning and lateral partitioning was proposed. The 1st generation substrates embedding square or hexagonal Si segments within polyimide were designed and fabricated. Mechanical qualifications were performed for the samples using specially designed and fabricated tensile and bending setups. FE simulations were performed to get more understanding of the occurrence of damage.

The 2nd generation substrates were designed and fabricated to investigate in particular the interconnections between the segments. Also the 2nd generation samples got certain improvements compared to the 1st generation samples. In particular, in the 2nd generation samples, the oxide layers that caused early failure in the 1st generation samples were omitted. The FE models and experiments on the 2nd generation samples were especially used to get insight into possible segment cracking and the failure behaviour of the interconnections.

Future flexible and stretchable substrates were proposed, where the polyimide was replaced by silicone rubber. In order to be able to perform adequate FE design simulations, the constitutive behaviour of the rubber material was obtained from mechanical characterizations. In a future flexible and stretchable substrate the interconnections were embedded within the silicone rubber. This only resulted in a moderate improvement with respect to the 2nd generation samples. To obtain further improvement of the flexibility a future flexible and stretchable
substrate II was proposed, where free standing interconnections were used, while the system had to be sandwiched between two silicone rubber sheets.

6.1.1 Design and fabrication of the flexible and stretchable substrates

The 1st generation flexible and stretchable substrates were created as a result of a preliminary design attempt to create small thin silicon based electronic segments that are embedded in a polymer material. The preliminary design was made for verification of the suitability of the fabrication concept and to test the stretch-ability, flexibility and the occurrence of failure during loading. Samples were designed with square and hexagonal partitions varying in segment size from 150 µm to 2000 µm and in gap size from 20 µm and 250 µm. (see section 2.2.1)

Poly-silicon (on a supporting wafer) was patterned into segments with square or hexagonal shapes by using photo-lithographic processes. The segmented poly-silicon (on a supporting wafer) was then covered with a thin polyimide layer. This structure was subsequently adhesively bonded to a temporary glass carrier using acrylic glue. After removal of the supporting wafer by wet etching, the segmented “ultra-thin silicon segments on a PI substrate” samples were peeled off from the temporary glass carrier. (see section 2.2.2), resulting in the final flexible and stretchable substrate.

As a result of the qualification tests and the supporting FE simulations it was found that cracking of the intermediate Si-oxide layers occurred as the major restriction of the flexibility of the 1st generation substrates (see Chapter 2). Therefore, in the design of the 2nd generation test structures the fabrication process was changed such that no Si-oxide layers remained on the polyimide within the gaps in between the Si-segments. Further, the process was adjusted to create interconnections of various types in between the poly-silicon segments. As a result metal layer tests structures (of aluminium) are integrated on the poly-silicon segments as well as on poly-silicon support structures bridging the gaps. Samples having various segment size (from 150 to 450 µm) and various segment spacing (from 20 to 200 µm) (see table 3.1) were created. Segments with rounded corners as well as with sharp corners were designed (see section 3.2.1). Two sets of bond pads are created at the end edges of the substrates. These are used for applying resistance measurements of the daisy chains of segments with interconnections. The aluminum wave-line interconnections between the segments were fabricated using the metallization process as described in section 3.2.2.
6.1.2 Mechanical qualification for the thin foils

Mechanical qualification of the flexible and stretchable substrate samples is challenging because various standard tests cannot be used. As an example, the substrates are too flexible to apply any lateral loading in common 3-point or 4-point bending tests. Therefore, to explore the suitability of the substrates to survive bending deformations, special bending test setups were designed and fabricated. Here the substrates are wrapped around test cylinders of various diameters. These test cylinders were made from glass to be able to observe the occurrence of cracking during the tests. The substrates are mounted on the test setup under a small pre-stress. In this manner the effect of substrate warpage is minimized and consequently a continuous contact between glass cylinder and substrate is assured. A microscope with digital camera was used to observe and monitor the occurrence of possible cracks (see section 2.3.2). This microscope could be rotated perpendicular to the glass cylinder surfaces.

To explore the suitability of the substrates to withstand stretching, a tensile test was used, where damage observation was again done using a microscope with digital camera. The tensile setup being used was specially designed and fabricated for testing these flexible and stretchable substrates. The tensile tool includes clamps, a micro-screw loading part, a force sensor and a displacement sensor. The force and displacement data are recorded by using of a data acquisition system. An optical microscope with CCD-camera and computer was used for monitoring the crack initiation and crack evolution. The displacement is manually controlled for the convenience of step wise loading and crack observation during the test (see section 2.3.2).

6.1.3 Experimental and FE failure analysis for the flexible and stretchable substrates

For the 1st generation flexible and stretchable substrates, the first crack appears on a silicon oxide layer in-between the segments under bending as well as for tensile loading. The first crack runs through the gaps and the segments for samples with hexagonal segments. However, for samples with square segments the first cracks are found in the silicon oxide layers within the gaps only, because the strain localization in the relatively soft gaps. The development of first cracks depends significantly on the silicon segmentation size and gap size. The first generation substrates are applicable on (single curved) surfaces with radii of 1 mm and larger. The crack density increased sharply with the strain at early stage and then increased slightly. The crack width increased steadily with loading for all substrates being tested. All cracks are more or less perpendicular to the tensile loading direction.
For the 2nd generation flexible and stretchable substrates, no damage of the segments was detected for the samples being bent around the cylindrical rod with 2 mm diameter. The resistance measurements did not show any resistance increase over the threshold value (= 5% resistance increase). The bending around the cylindrical rods for the 2nd generation samples is not critical. The mechanical reliability of the 2nd generation samples under tensile loading is significantly improved. Compared to the 1st generation samples, for tensile testing the (mean) strain at onset of failure (=segment cracking) appears to be significantly improved. As an example, for the case with segments 150x150 μm and 20 μm gap size the improvement is 260%. Nevertheless, the limiting (mean) strain is yet relatively low (1.86% only).

Because of the large ratio of width (or length) to thickness, for the 1st generation substrates, a global-local FE model was used for the mechanical simulations. Here the substrates (both for the hexagonal and the square case) were modelled with overall models with relatively coarse meshes with “equivalent” material properties as obtained from more detailed analysis of chosen “unit cell domains”. The unit cell domains were further used for more detailed stress analysis, applying the boundary displacements as established with the overall models. Experimental and simulation results for the onset of cracking appear to be consistent. The first cracks appear in the oxide layers in the gaps between the silicon segments. Only at higher (mean) deformations they propagate or are generated within the silicon itself. The onset of cracking depends significantly on the silicon segmentation size.

For the 2nd generation samples it was decided not to perform global-local FE simulations of the substrates, because the oxide layer (that previously was shown to crack in the 1st generation samples) was omitted. Instead the FE simulations were focussed on the interconnection shapes only. From comparison of FE simulation results and electrical degradation data from the experiments it was found that the reaching of the ultimate strength in the aluminium (at a local spot only) is not well correlated to the degradation of the electric conductivity. Therefore, it is suggested to consider the “total work of plastic deformation” over the “total work of elastic deformation” as a measure that could eventually be connected better to the change in elastic conductivity in future work.

For the 2nd generation samples various parameter sensitivity analyses were established (Chapter 3) for the metal-line interconnections (based on an “ultimate strength criterion”). From these analyses it is found that the (allowable) sample mean strain increases with decreasing interconnection width (for a sample with amplitude 40 μm and number of half waves=2). The
sample mean strain increases with increasing wave amplitude (for a sample with interconnection width=2 μm). A minor influence of the number of half waves is observed. For the future generation samples sensitivity analyses for metal-interconnections are described in Chapter 4 and 5.

6.1.4 Mechanical characterization of silicone rubber

For the future flexible and stretchable substrate concept I (as described in Chapter 4) a relative soft embedding material was proposed. For this purpose a silicone rubber was selected. For the accompanying FE simulations a material constitutive relation for this silicone rubber is necessary. In order to establish a suitable constitutive relation tensile tests on fully cured silicone rubber foil were performed. At room temperature visco-elastic effects of fully cured silicone rubber appear to be negligible as the stress-strain behaviour stabilizes after a few cycles. The glass transition temperature \( T_g \) is found at -45.35°C (\( T_g \) is here defined as the temperature where the max viscous damping is established, for DMA testing at 1 Hz). From a single tensile test a failure strain of about 176% was found. The rubbery plateau (Young’s) modulus of the silicone rubber turns out to be \(~1.70\) MPa (for temperatures above \(~-15°C\)).

For the FE simulations we used Mooney-Rivlin types of constitutive models being fitted to the established stress-strain data. The adequacy of these models was tested by verification on experimental results of a double shear test.

6.1.5 Free-standing interconnection design

The future flexible and stretchable substrate concept II was discussed in Chapter 5. Here free-standing interconnection copper lines, being sandwiched in between silicone rubber sheets (without mechanical contact), are proposed. Here meander, horseshoe and mesh stretchable structures were considered. In order to explore the stretchability of the various structures FE simulations were performed. As each type of structure was created by repeating a base element having a set of parameters (width of the metal line, spacing between metal lines, angles and radius of curvature) the FE simulations could be restricted to the base elements with appropriate symmetry/continuity conditions.

The maximum mean strain of the substrate is limited by the maximum elongation of the silicone rubber protection sheets, being 176%. At this mean strain, for the most favourable case
(being a meander structure with $W=5\ \mu m$, $R=100\ \mu m$ and $\alpha=30\ \text{degree}$) the established equivalent strain in the copper is found to be $6.439e^{-3}$ only. This is below the elastic strain limit of the Copper. As a result, this meander interconnection will behave fully elastic and thus will not be damaged, even not under cyclic elongation.

6.2 Conclusions

Because the project duration was limited, at the end of the project flexible and stretchable substrates with electronic functions included were not yet designed and fabricated.

Both the experiments and the FE simulations on 1st and 2nd types of flexible substrates showed insufficient stretchability because of early occurrence of cracking. Further, the interconnections as tested in the 2nd generation samples showed relatively early electrical degradation. It was concluded that this was caused by the embedment of the segments and interconnections into the relatively stiff polyimide. For this reason for next generation substrates it was the 1st proposed to use much softer material for the embedment of the segments and their interconnections. As a much softer embedding material for a 1st concept of future substrates a silicone rubber was proposed. From FE-simulations it was concluded that even with such a soft material the improvements in flexibility were disappointing. It was concluded that this disappointing behaviour was originating from the fact that the interconnecting structures could not freely act as spring structures due to the embedment in another material. Therefore, the idea of sandwiching free standing spring structures within silicone rubber protection foils, without mechanically contacting such foils, was further explored through FE simulation. This resulted into a 2nd concept of future substrates. It was shown that this concept is quite promising. Because of the limited project duration, this concept could not be further worked out fabricated and thus is presently considered as recommended future concept.

6.3 Recommendation

As a major recommendation of the project, the concept of sandwiched silicon segments with free standing interconnection spring structures within Silicone rubber sheets should be further worked out, fabricated and tested in a next project.
Appendix A: Equivalent material properties

The “equivalent” mechanical properties of “Representative Unit Cell” have to be obtained in order to create Global-local FEM models for the flexible and stretchable substrates. The unit cells selected are made up from a silicon segment in the centre, surrounded by gap materials plus some parts of the surrounding segments as well. A quarter of segment is selected because of symmetry.

Fig.1. Representative unit cell

a. square segments  

b. hexagonal segments

The boundary conditions include fixed x-direction displacement of node s at the left hand boundary (AC), x-direction force loading of nodes at right hand boundary (BD), the y-direction displacements of nodes of the top (AB) and bottom (CD) sides are the same because of symmetry in the sample. The material properties for silicon, silicon oxide and polyimide are shown in detail in Table 2 in Chapter 2.

The mean stress can be obtained through the force and sample cross section area, the strain can be obtained through the displacement in simulation and the length in undeformed state. The equivalent young’s modulus and poisson ratios for the flexible and stretchable substrates can be obtained by stress and strain. The following table shows the equivalent mechanical properties in detail.
Table A.1 The equivalent mechanical properties for the 1st generation samples

<table>
<thead>
<tr>
<th>segment</th>
<th>segment size (µm)</th>
<th>Gap size (µm)</th>
<th>Equivalent Young’s modulus</th>
<th>Poisson ratios</th>
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<td>Square segment</td>
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<tr>
<td></td>
<td>300</td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td>600</td>
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<td>0.230176</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>250</td>
<td>4.691165</td>
<td>0.232682</td>
</tr>
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<td>Hexagonal segment</td>
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</tr>
<tr>
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<td></td>
<td>600</td>
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<td>4.783308</td>
<td>0.23789</td>
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</table>
Samenvatting

Conventionele IC-packages vormen een starre omhulling rondom silicium chips. Hun doel is het verschaffen van bescherming tegen omgevingsinvloeden, het voorzien in elektrische verbindingen en de verspreiding van warmte. Ondanks het feit dat de meerderheid van de huidige silicium IC’s in een zeer dunne bovenlaag van de silicium substraat (<10 µm) zijn ingebed is de gebruikelijke dikte van de chips over het algemeen meer dan 150 µm. De voortdurende systeemminiaturisatie en prestatieverbetering leidt tot nieuwe massa-volume toepassingen, waarbij de omkapselingstechniek van de IC’s opnieuw bekeken dient te worden. Alleen het essentiële deel van de silicium toplaag van 10-20 µm zou kunnen worden behouden na het verdunnen van de wafer. Bij een waferdikte beneden de 10-30 µm worden de silicium substraten mechanisch flexibel en als het gevolg daarvan ontstaan nieuwe mogelijkheden voor producten en innovatieve toepassingen.

Een veelbelovende ontwikkeling van flexibele en rekbare substraten wordt voorgesteld. 3D vervormbare elektronica zou kunnen worden gerealiseerd door een dunnere silicium laag te gebruiken en deze op submillimeter schaal in stukjes (partities) te verdelen. De partities of de zogenaamde segmenten kunnen worden gecombineerd tot grotere electronische systemen door deze elektrisch met elkaar te verbinden. Door de partitie afmetingen en de geometrie van de verbindende elektrische bruggen te variëren, kan het niveau van deformatie worden gecontroleerd. In de praktijk zullen dergelijke gepartitioneerde silicium structuren moeten worden ingebed in een polymeer film om te zorgen voor bescherming en om mechanische beschadiging als het gevolg van sterke vervorming te reduceren.

Om de invloed van de segment afmetingen en hun onderlinge afstanden op het ontstaan van beschadiging tijdens buigen en oprekken te onderzoeken, werd een eerste generatie “flexibele en rekbare” proefstukjes ontworpen en gefabriceerd. De beschouwde proefstukjes hebben hexagonale of vierkante partities (variërend in segment afmetingen van 150 tot 2000 µm) die zijn ingebed in polyimide. Speciale trek- en buig testfaciliteiten werden ontworpen en gefabriceerd om het optreden van scheuren tijdens vervorming te kunnen observeren. Een microscoop met de mogelijkheid om digitale beelden op te nemen en te analyseren is gebruikt.
om de scheurdichtheid en -breedte vast te stellen. Uit de experimenten en uit begeleidende simulaties verkregen resultaten aangaande scheurinitiatie zijn zeer teleurstellend. Getoond wordt dat de eerste scheurtjes verschijnen in de oxide lagen ter plaatse van de openingen tussen de silicium segmenten. De scheurdichtheid blijkt al in een vroeg stadium van de belasting sterk aan te groeien, gevolgd door een wat geringe stijging. Echter, de scheurbreedte blijkt continu aan te groeien tijdens belasting. Alleen bij relatief grotere (gemiddelde) deformaties groeien de scheuren (of initiëren) zij in de silicium segmenten. Het moment van scheurinitiatie hangt zeer sterk af van de afmetingen van de silicium segmenten. De segmentafmetingen en onderlinge afstanden beïnvloeden ook de scheurdichtheid en scheurbreedte bij grotere (gemiddelde) deformatieniveaus. Er zijn geen scheuren gevonden bij buiging om glazen cilinders met een diameter van 2 mm (de kleinste proefdiameter) voor proefstukjes met vierkante segmenten met een zijdelengte van 450 μm en onderlinge afstand van 120 μm en voor proefstukjes met hexagonale segmenten met een zijdelengte van 300 μm en onderlinge afstand van 40 μm. De resterende buigproefresultaten laten zien dat bij andere proefstukjes met vierkante segmenten, scheurvorming altijd optreedt bij de buiging om glazen cilinders met een diameter van 2 mm. Uit zowel de trekproeven als ook uit de simulatieresultaten volgt dat scheurvorming in de oxide lagen de rekbaarheid van de substraten sterk beperkt.

Als gevolg van de vroege schadeinitiatie bij de eerste generatie proefstukjes, is een gomodificeerd ontwerp voorgesteld en verder uitgewerkt. Deze tweede generatie proefstukjes werd ontworpen en geproduceerd met volledig gesegmenteerde polykristallijne silicium segmenten met flexibele aluminium verbindingen die worden ondersteund door polykristallijne silicium structuren. De beschouwde proefstukjes hebben segmentafmetingen varierend van 150 tot 450 μm en segmentafstanden varierend van 20 tot 200 μm. Verscheidene (min of meer) sinusvormige verbindingen werden gekozen met gevarieerde aantallen halve golflengtes en golfamplitudes. Wanneer de proefstukken werden gebogen om de glas cilinder met een diameter van 2 mm, werd geen schade aan de segmenten ontdekt. Weerstandsmetingen laten geen weerstandstoename groter dan 5% zien. Vergeleken met de eerste generatie proefstukken blijkt dat voor trekproeven de (gemiddelde) rek bij aanvang van falen (bij de 2e generatie proefstukjes is dat scheurinitiatie in de segmenten) significant verbeterd te zijn. Om meer inzicht te verkrijgen in het optreden van falen in de elektrische verbindingen, zijn verscheidene EEM simulaties uitgevoerd voor golfvormige verbindingen in proefstukjes met vierkante segmenten (alleen voor rek). Het toegepaste lokale model bestaat uit een metalen verbinding met polykristallijne silicium ondersteuningsstructuur, ingebed in polyimide. Vergelijking van de
Samenvatting

experimenteel verkregen rekwaarden bij de weerstandsverandering van 5% met de “gemiddelde rek” bij (verondersteld) aanvang van falen, gaf geen goede overeenkomst. Klaarblijkelijk is de veronderstelde aanvang van falen, hier gedefinieerd door het bereiken van de treksterkte in de aluminium (dat alleen optreedt in een lokaal gebied) geen goede maatstaf voor de vermindering van het elektrisch geleidingsvermogen. De “arbeid door plastische vervorming” zou wellicht beter correleren met de weerstandsverandering. De sinusvormige elektrische verbinding blijkt beter resistent tegen weerstandsverandering dan de rechte en de halfcirkel vormige verbinding. De invloed van de golfamplitude, aantal halve golflengtes en de lijnbreedte van de sinusvormige verbindingen zijn onderzocht. Echter, de gemiddelde rek bij aanvang van elektrisch falen blijkt begrensd te zijn tot slechts een paar procent. Uitgaande van de experimentele- en de simulatieresultaten is geconcludeerd dat onvoldoende flexibiliteit is verkregen voor al de beschouwde verbindingen. Verondersteld is dat dit wordt veroorzaakt door de inbedding van de verbindingen in polymide. Om deze reden is in hoofdstuk 4 inbedding in een veel zachter materiaal uitgewerkt. Ook het geval van een geheel vrije verbinding (niet ingebed) wordt bekeken (hoofdstuk 5). Op deze wijze worden nieuwe concepten voor “toekomstige flexibele en rekbare substraten” geïntroduceerd.

In het concept van “toekomstige flexibele en rekbare substraten I” (hoofdstuk 4) zijn de segmenten en verbindingen ingebed in siliconenrubber. Adequate materiaalmodellen voor siliconenrubber zijn essentieel voor het verkrijgen van inzicht omtrent het mechanische gedrag van het nieuwe ontwerp met behulp van EEM simulatie. In het bijzonder wordt EEM simulatie toegepast voor het voorspellen van mogelijke falen. De mechanische eigenschappen van siliconenrubber werden gekarakteriseerd door verschillende methoden, waaronder (cyclische) trekproeven en Dynamisch Mechanische Analyse (DMA). De breukrek van siliconenrubber bij kamertemperatuur kan ongeveer 176% bereiken. Visco-elastisch gedrag van siliconenrubber bij kamertemperatuur is niet relevant. Als constitutief model van siliconenrubber in de EEM simulaties is gekozen voor het derde orde Mooney model.

Gebaseerd op de EEM simulatieresultaten voor de “toekomstige flexibele en rekbare substraten I” is het te verwachten dat bij verhoging van de gemiddelde rek, eerst het silicium zal falen en vervolgens het siliconenrubber. Het falen van de Si-segmenten zal waarschijnlijk niet plaatsvinden. In vergelijking met de tweede generatie substraten geeft het concept “toekomstige flexibele en rekbare substraten I” slechts een verbetering van ongeveer een factor twee ten aanzien van het reknivo bij falen. De beperkende factor voor verbetering is het teleurstellende gedrag van de Si- ondersteuningsstructuur. Blijkbaar vermindert de inbedding in rubber sterk het
“verend” gedrag van de sinusvormige ondersteuningsstruktuur. Daarom is een substantiële verbetering voorgesteld in het concept voor “toekomstige flexibele en rekbare substraten II”, door de elektrische verbindingen niet volledig in te bedden in Si rubber, maar om deze structuur slechts in te passen tussen twee Si-rubberen folies.

Voor het concept “Flexibele en rekbare substraten II” zijn de gegolfde aluminium elektrische verbindingen vervangen door koperen golfverbindingen, vanwege de betere mechanische en elektrische eigenschappen van koper. Vrijstaande koperen verbindingsschermen (zonder ondersteuningsstructuren) afgedekt door twee Si-rubber folies verbinden nu de Si-segmenten. Drie typen van verbindingen, meander vormig, hoefijzer vormig en gaasvormig met verschillende sets van parameters werden ontworpen. Simulaties aan deze basis onderdelen werden uitgevoerd om de invloed van de geometrische parameters met betrekking tot de flexibiliteit en rekbaarheid te evalueren. De vrijstaande verbindingsschermen en hun geometrische parameters hebben een significante invloed op de rekbaarheid. Uit de drie typen verbindingen die zijn onderzocht blijkt het meandervormige ontwerp het meest gunstige te zijn. In vergelijking met de resultaten voor het concept “toekomstige flexibele en rekbare substraten I” kan geconcludeerd worden dat een grote verbetering ten aanzien van de rekbaarheid van de verbindingenstructuur is gevonden. Het is te begrijpen dat door de grote flexibiliteit van de meandervormige verbindingen, de maximale gemiddelde rek van het substraat wordt beperkt door de maximale gemiddelde rek die andere delen kunnen doorstaan. Hierbij opgemerkt dat de breukrek van de silicon rubberen folies beperkt is tot ongeveer 176%. Met deze verlengingslimiet zal de gunstige meandervormige verbinding (W=5 μm, R=100 μm en α=30 graden) zich volledig elastisch gedragen en zal niet worden beschadigd, zelfs niet bij cyclische verlenging.
First of all my unconditional love and gratitude to my family. I wish to heartily thank my dear wife Zou Suqin, who waited for me more than two years before joining me in Holland. I thank her for all the love and encouragement and the endless unconditional support in all my professional and private endeavours. I thank my parents for bringing me up and preparing me for my independent life. I also would like to thank my sister, brothers and their family while we all are far from home.

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About the Author

Lingen Wang was born in Wanzai, Jiangxi province in China on Dec. 14, 1974. He received his Bachelor of Science in Mechanical Engineering from Hebei University of Engineering in 1999 and Master of Science in Master in science in Mechanical Engineering from Guilin University of Electronic Technology in 2002, China. His master graduation project was Mechanical reliability study of flip-chip package by FE modeling. He joined “Engineering Mechanics” research group in Faculty of Design, Engineering and Production in Delft University of Technology in the Netherlands after graduation. His field was epoxy molding compound characterization. He started to work toward his Ph.D degree in the field of “Electronic flexible and stretchable substrates” in May 2004. Currently he is working for Boschman Technologies in the field of MEMS encapsulation and wafer level molding.
PROPOSITIONS
Accompanying the thesis
Mechanical Characterization of Flexible and Stretchable Electronic Substrates
of
Lingen Wang

1. Flexible substrates can be subdivided in two classes:
   Substrates that allow for inextensial bending only and substrates that due to the larger stretchability allow for more arbitrary bending.
The first group of flexible substrates can only be applied on surfaces with zero Gaussian curvature. The application of the second group of flexible substrates is more general. They can also be applied on doubly curved surfaces. Therefore, the applicability of the second type of flexible substrates will be more general.

2. In engineering, cooperation and communication are more important than conducting experiments and simulations.

3. Plastic strain cannot be used as a measure in a criterion for degradation of the electric conductivity of a metal interconnection (see Chapter 3 of this thesis).

4. Silicone rubber is more suitable as an embedment material in stretchable substrates than polyimide (see Chapter 4 of this thesis).

5. Stretchable substrates that are based on a concept of silicon segments with free-standing interconnections being sandwiched between silicon rubber foils will be advantageous compared to substrates with complete embedment within silicon rubber or polyimide.

6. As technology develops continuously, people do not need to work 5 days a week anymore to solve society problems.

7. The GDP (Gross Domestic Product) is often considered as a basic measure of a country’s overall economic performance. However, there is no direct relation between the GDP and the profitability of companies and/or personal actions within a country. Therefore a high GDP does not correlate to the welfare of its inhabitants.

8. The Dutch government has apparently reasons to change over from the present partly fixed and partly energy dependent road tax system to a system that is partly energy dependent and partly driving distance dependent. However, the change in system finally will not solve any problem. The only outcome will be that everyone pays more and the government income will rise.

9. When all countries build electronic driving distance dependent road tax systems separately, travelling through more countries will be hindered by the fact that different electronic registration systems must be installed and used. This development will degrade economic growth and conflicts with the European Union’s basic principle of free travelling.

10. A energy dependent road tax system does not work if the vehicle energy can be taken a source that is not controlled by the government, such as from local wind energy.

These propositions are considered opposable and defendable and as such have been approved by the Promoter Prof. dr. ir. L.J. Ernst.
1. Flexibele substraten kunnen in twee groepen worden onderverdeeld:
   Substraten die alleen rekloze buiging toelaten en substraten die door de grotere rekbaarheid ook andre vormen van buiging toelaten.
   De eerste groep flexibele substraten kunnen alleen worden aangebracht op oppervlakken waarbij de Gaussse kromming nul is. De toepassing van de tweede groep flexibele substraten is meer algemeen van aard. Zij kunnen ook worden toegepast op dubbel gekromde oppervlakken. Hierdoor is de toepasbaarheid van deze klasse substraten meer van algemene aard.

2. In engineering zijn samenwerking en communicatie belangrijker dan het uitvoeren van experimenten en simulaties.

3. Plastiche rek kan niet als maat worden gebruikt in een criterium voor de degradatie van elektrische geleiding van een metalen interconnectie.

4. Siliconen rubber is meer geschikt om te worden gebruikt als een inbeddingsmateriaal in rekbare substraten dan polyimide (zie hoofdstuk 4 van dit proefschrift)

5. Rekbare substraten die gebaseerd zijn op het concept van silicium segmenten met vrijstaande interconnecties, gesandwiched tussen siliconen rubberen folies zullen voordeel bieden ten opzichte van substraten met volledige inbedding in siliconen rubber of polyamide.

6. Aangezien technologie zich voortdurend ontwikkelt, hoeven mensen niet meer 5 dagen in de week te werken om maatschappelijke problemen op te lossen.

7. Het nationaal bruto product (NBP) wordt vaak als een basis maat gezien voor de nationale economische prestatie van een land. Echter, er is geen direct verband tussen het NBP en de winstgevendheid van bedrijven en/of persoonlijke acties binnen een land. Als gevolg hiervan correleert een hoog NBP niet met de welvaart van diens inwoners.

8. De Nederlands overheid heeft klaarblijkelijk redenen om over te stappen van het huidige deels vaste en deels energiegerelateerde wegenbelastingssysteem naar een systeem dat deels energiegerelateerd en deels afgelegde weg gerelateerd is. Echter, de verandering zal geen enkel probleem oplossen. Het enige resultaat zal zijn dat iedereen meer zal betalen en de overheidsinkomsten zullen groeien.


10. Een energieafhankelijk wegenbelastingssysteem werkt niet als de voertuigenenergie kan worden verkregen uit een bron die niet door de overheid wordt gecontroleerd, zoals van locale windenergie.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor Prof. dr. ir. L.J. Ernst.